



U. S. Department of Energy Environmental Control Symposium

Washington, D. C., November 28-30, 1977

PROCEEDINGS

Volume 3 of 3. Solar Energy,
Geothermal Energy, and Waste
Heat Transmission

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Control Symposium

**November 28-30, 1978
Washington D.C.**

Volume 3. Solar Energy, Geothermal Energy, and Waste Heat Transmission

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Office of Environmental
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U.S. Department of Energy

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Environmental Control Symposium sponsored by the Department of Energy (DOE). Although the symposium was organized under the auspices of the Environmental Control Technology Division, Assistant Secretary for Environment, Symposium presentations highlighted environmental control activities which span the entire Department of Energy.

The plenary session topic, "Energy and Environmental Goals: Compatibility through Environmental Controls," reflects the Department of Energy's goal and commitment to the support and development of energy systems that are environmentally acceptable. This commitment is, in part, shown by the extensive support of environmental control activities within the total DOE program: about \$300 million in FY 1978*, with a similar amount anticipated for FY 1979.

The objectives of the Environmental Control Symposium were: (a) to emphasize that, concurrently with the development of energy technologies, DOE is deeply concerned with the corollary measures required to mitigate potential impacts on the environment from existing and new energy systems; and (b) to provide a forum for the dissemination of information and achievements of DOE activities in the area of environmental control. For this reason, the Symposium presentations focused on DOE-supported activities related to research, development, and demonstration of processes, procedures and strategies to eliminate or reduce undesirable environmental impacts of energy technologies. Rather than simply identifying potential problem areas, the presentations were intended to emphasize results of ongoing efforts. Symposium topics included discussions of (a) simple "add-on" control methods for application to conventional and possibly emerging power systems; (b) in-process modifications to energy production techniques to control environmental impacts; (c) alternative energy systems; (d) environmental control aspects of energy transmission, transportation, and storage; and (e) alternative energy and environmental control strategies.

Owing to the varied topics covered in the Symposium and the total length of the papers presented, these proceedings have been arranged into three volumes, whose contents correspond to selected areas of interest. The arrangement is as follows:

Volume 1 - Plenary Session and Fossil Fuels

- Session 1 - Plenary Session
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* *Environmental Control Technology Activities of the Department of Energy in*

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Session 4 - Environmental Control Considerations in Geothermal
Energy Utilization

Session 5 - Environmental Control Aspects of Solar Energy Usage

Session 8 - Environmental Control Aspects of Solar Power Generation

Session 13 - Power Transmission and Energy Storage Systems

Session 16 - Energy Conservation - Waste Heat Utilization

The Department of Energy feels that this first Symposium and subsequent symposium now being organized will provide a forum for enhanced information exchange between the Department and the public on its progress toward the goal of ensuring that the Nation's energy demands can be met in an environmentally acceptable manner.

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(U.S. Department of Energy unless otherwise indicated)

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5	John Mock Energy Technology	M. R. Riches Energy Technology
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ENVIRONMENTAL CONTROL CONSIDERATIONS IN GEOTHERMAL ENERGY UTILIZATION

Chairman: Allan Jelacic

Co-Chairman: Douglas Boehm

IDENTIFICATION OF ENVIRONMENTAL ISSUES ASSOCIATED WITH THE UTILIZATION OF GEOTHERMAL ENERGY

Lynn R. Anspaugh
Lawrence Livermore Laboratory

Geothermal energy, the stored heat of the earth, is a major resource and can make a significant contribution to the nation's energy supply in the future. Three types of resources are of near-term interest--hydrothermal convection systems, hot-dry rocks, and geopressured systems. The utilization of hydrothermal convection systems has been demonstrated throughout the world, and the environmental problems are well known. They consist of the release of noncondensed vapors and gases, primarily hydrogen sulfide, to the atmosphere; the safe disposal of large amounts of spent geothermal fluids; the possible occurrence of land subsidence and enhanced seismic activity; the production of high levels of noise; and general problems involving social, cultural, economic, and political issues. Problems at any particular site will be highly dependent upon local conditions such as reservoir characteristics and the nature of the local region. Energy extraction systems have not yet been fully demonstrated for hot-dry rock or geopressured systems. However, we can anticipate that essentially the same environmental problems will be encountered with the same site-specific nature of the severity of the problems.

OVERVIEW OF H_2S CONTROL TECHNOLOGY FOR GEOTHERMAL ENERGY SOURCES

K. P. Ananth

Midwest Research Institute

This paper briefly discusses the control of H_2S emissions from geothermal power plants. The control options, as presented here, are primarily directed toward: (i) incoming steam (i.e., upstream), (ii) condenser vent emissions, and (iii) cooling tower emissions. For each category, the major processes are identified along with their advantages and disadvantages. Finally, the processes are intercompared using several selection criteria. These criteria include stage of development of the control technology, its potential for H_2S removal, extent of applicability, cost of control, and secondary environmental

EIC Corporation, with support from the Department of Energy and Pacific Gas and Electric Company, has been engaged in the development of a process for the removal of hydrogen sulfide from geothermal steam.

The development effort has been carried out in a three phase program which includes fundamental studies at the laboratory scale to define the basic chemistry of the process and to obtain preliminary design data, an engineering design and development effort to demonstrate the applicability of the process on real geothermal steam and to develop the design of a demonstration plant, and the construction and operation of an integrated demonstration plant for the process at a 5 MW scale.

The process, which removes hydrogen sulfide at turbine upstream conditions, is based on the chemistry of the acid copper sulfate-hydrogen sulfide system. The essential steps in the process include contacting the steam with copper sulfate solutions, separating the reaction products to purge soluble impurities and to direct the precipitated copper sulfides to regeneration, and regeneration of copper sulfate for recycle.

In this paper, we will describe the development program which has been carried out and the current status of the demonstration plant. The experimental and analytical work which has been carried out and the preliminary process design criteria for the process will also be presented.

REMOVAL OF H_2S FROM GEOTHERMAL STEAM BY CATALYTIC OXIDATION

Charles T. Li and Richard A. Brouns
Battelle Pacific Northwest Laboratories

The removal of H_2S is necessary for preventing the corrosion of equipment and protecting the environment if geothermal steam is to be utilized for the power generation. A catalytic oxidation to remove H_2S from geothermal steam has been studied in a laboratory bench scale unit. The process uses an old H_2S removal technique in which H_2S is oxidized by O_2 (or air) to form H_2O and elemental sulfur in presence of activated carbon as a catalyst. The process has been proved to be a feasible one in our laboratory. It removes H_2S in simulated geothermal steam from 200 ppm to lower than 20 ppm most of the time. The spent carbon can be regenerated and reused. The next phase of work will be the design of a pilot plant and the evaluation of the process by actual field tests.

Under the direction of the Department of Energy (DOE), the development of various new energy sources is moving ahead. Associated with these sources are various problems. One such problem is land deformation that may accompany removal or injection of fluids from or into geothermal reservoirs. The issue of land deformation, commonly referred to as subsidence, is the focus of this research program plan.

Unexpected and uncontrolled subsidence may have social, environmental, and economic consequences. However, subsidence occurring under controlled conditions may be acceptable. The impacts can vary greatly, based on geological and land-use settings. The degree of concern attached to subsidence will depend on an assessment of subsidence potential at each geothermal site. The Subsidence Control Research Program seeks to enable such assessments to be made with a degree of confidence.

The objective of geothermal subsidence research is to control or mitigate potential subsidence associated with geothermal development within predictable limits. In this way, geothermal programs may proceed without delays and site flexibility may be increased.

Successful subsidence research will provide: 1. The means for development to build and operate geothermal facilities within prescribed limits of potential subsidence. 2. The basis for policy makers to regulate geothermal facilities with respect to potential subsidence.

The subsidence Control Research Program is an integrated structure consisting of five major elements:

A. CHARACTERIZATION OF SUBSIDENCE - This element is concerned with the measurement of subsidence and subsidence effects. The intent of its research categories is to characterize the subsidence phenomenon or provide the means to attain that characterization.

B. PHYSICAL THEORY OF SUBSIDENCE - This element involves assessing current theory about the physical processes of subsidence and to correct deficiencies in that theory. The theoretical studies will include both the response of geologic materials to stress fields and the nature of induced movements along fracture systems.

C. PROPERTIES OF MATERIALS - Subsidence is a response of geologic materials to some external perturbation such as the removal of geothermal fluids.

D. SIMULATION OF SUBSIDENCE - Simulation includes the mathematical modeling of subsidence and related phenomena. It is the useful application of physical theory. One or more reliable subsidence models comprise an essential element of the overall research program.

E. SUBSIDENCE CONTROL - The last element is the target element of the research program. The other elements provide the supporting information needed to make the program goals attainable: 1. Distinguish naturally occurring subsidence from that possibly caused by geothermal operations; 2. Operate a geothermal well field in a manner that will prevent or minimize adverse effects due to subsidence.

This study considers the impact of human disturbances, as might be found during geothermal development, on a nesting population of the ferruginous hawk (Buteo regalis) in Raft River Valley, Idaho. This species is reportedly sensitive to environmental disturbances. Treatment nests were impacted by discharging firearms at various distances from the nest (=3), driving toward nest in vehicles (N=3), approaching nests on foot (N=3), and by placement of continuously running motors near nests (N=2). During the treatment period, May 3 - July 17, nests were approached only to the point at which the adult flushed from the nest. Flushing distances were recorded to indicate a level of disturbance constant at all nests. The flushing distance varied from 4.6 to 484 meters, with considerable variation between nests but more uniformly within nests on repeated treatments. Increasing sensitivity or tolerance to the treatment through time was not evident. Three nests, two walk-to and one drive-to, were deserted after 10, 14, and 8 days of treatment respectively. Wind destroyed one nest and predation destroyed a second. Control nests (N=16) were not approached, nor, in some cases, located until the young were about three weeks old and ready to band. The control nests fledged 55 young, for a fledging rate of 3.44 young per nest. Successful treatment nests (N=6) produced 17 young, for a fledging rate of 2.83 young per nest. By paired comparison (T-test), the differences were not significant ($T > 0.1$), but the differences may be nonetheless of biological significance. A fledging rate of all treatment nests was 1.88 young per nest, which is significantly different from the control ($p < 0.05$). Adults were clearly more attentive at control nests than at treatment nests when the young were two to three weeks old.

Differences in fledging success are considered a result of the human impact and not other variables such as food source, etc. The rabbit population, which made up 89% (by biomass) of the prey remains found in nests, averaged 309 individuals per km², for 16 km of transect. Smaller rodents averaged 32 individuals per 1200 m² for 1600 trap nights. By contrast, fewer nests were active in adjacent Curlew Valley, where the rabbit density was 50 individuals per km² and the five active hawk nests produced only 3.0 young per nest.

A mutualistic relationship was found between ferruginous hawks and Swainson's hawks. The latter nested on the average 0.6 km from 14 of 15 active ferruginous nests, while only 3 of 15 inactive ferruginous hawk territories had Swainson's hawk nests in them. Sources of error and unmeasurable variables affecting the results of such a study are several, including clutch size, individual differences, weather, undocumented disturbances, previous experiences of the hawks, our inability to accurately measure stress or anxiety, etc. These are discussed.

The ferruginous hawk is considered a good barometer of disturbance and will desert nests after repeated disturbances between 400 to 800 meters of the nest. We consider that the rate of desertion and level of sensitivity may be a direct function of the food base.

Lynn R. Anspaugh

Lawrence Livermore Laboratory

Paper not submitted for publication in Proceedings.

1. INTRODUCTION

One of the pollutants of major concern from geothermal energy systems is H_2S . At present, there are several H_2S removal processes; however, only a few have been successfully demonstrated for geothermal applications. Therefore this study was undertaken by Midwest Research Institute for the Department of Energy to conduct an overview of the available H_2S removal processes and to identify those that are most promising.

2. DISCUSSION OF CONTROL TECHNOLOGY

H_2S control technology for geothermal power plants can be classified into three categories. These may be listed as:

- a. Upstream controls - this refers to removal of H_2S ahead of the conversion process. Either vapor or liquid phase treatment may be required, depending on whether the geothermal resource is vapor-dominated or liquid-dominated.
- b. Vent controls - this category refers to processes which can be used for H_2S removal from non-condensable gas streams.
- c. Condensate/cooling water technology - this category refers to removal of H_2S from liquid streams.

Processes that fall into each of the above categories are briefly discussed below and then evaluated using a set of selection criteria to identify the most promising processes.

Upstream Control Technology

A number of techniques have been attempted for removal of H_2S ahead of the conversion process. Several of these appear promising, but all are in the development stages at this time. Those upstream processes which have been applied to geothermal fluids are summarized in Table 1 and discussed below.

The EIC process has been field tested at the Geysers with an 8 in. sieve tray scrubber. Efficiencies of the order of 97 percent were achieved. Based on cost information reported by the EIC Corporation^{1/}, the total annual power generation costs are reported to be about 2 mill/Kwh for a 100 MW plant and an H₂S concentration of 830 ppm^{2/}.

Table 1. H₂S Removal Processes for Control Upstream of Power Plant

For Vapor-dominated Systems

- * EIC Process
- * Deuterium Process
- * Solid Sorbent Process

For Liquid-dominated Systems

- * Dow Oxygenation Process

Deuterium Process: The Deuterium Corporation has installed and tested a device to remove H₂S from the geothermal fluid before it reaches the plant. A pilot test unit having an estimated capacity of 1000 lb/hr (steam) was tested at the Geysers Unit 7. Early test results indicated a removal efficiency of 90 percent^{3/}.

The Deuterium process is believed to use a liquid absorption scrubber but process details and the chemical reaction used are considered proprietary.

Solid Sorbent Process: Battelle Pacific Northwest Laboratories has investigated numerous metal oxides and organic amine sorbents for H₂S removal from geothermal steam. Among the solids tested, zinc oxide (ZnO) produced the most favorable results.

The process involves oxidation of H₂S with ZnO and subsequent regeneration of ZnO by oxidation of the zinc sulfide. It is reported^{2/} that Battelle's investigation recommends no further work on solid sorbents, since the process is not economically viable.

smaller static mixers. At this time, most work has been done in the laboratory using simulated geothermal fluids. Early results have been encouraging; at a mole ratio of injected oxygen to H_2S of 1.5, essentially all of the H_2S (90 to 100 percent) is removed within a 1 min. reaction time. The biggest problems appear to be corrosion and the potential for SO_2 release.

Total annual cost for power generation is reported to be 9 mill Fwh, based on 100 MW plant and 500 ppm H_2S ^{a/}.

H_2S Controls for Vent Gases

Available processes for removal of H_2S from vent gases are listed in Table 2. Among those listed in the table, the major processes are the Stretford Process, the Jefferson Lake Process and the Burner-Scrubber Process. The other processes are still in their early stages of development, with not much information being available. Therefore, they will not be discussed here.

Table 2. Control Processes for H_2S Removal from Vents Gases

- * Stretford Process
- * Jefferson Lake Process^{a/}
- * Burner-Scrubber Process
- * Ferrox Process^{b/}
- * Caustic Soda Process^{b/}
- * Sodium Hypochlorite Process^{b/}
- * Potassium Permanganate Process^{b/}

a/ This is a variation of the Claus Process.

b/ These processes are still in their early stages of development and are not considered promising, at the present time, based on available information.

disulfonic acid (ADA) to scrub the H_2S gas. The scrubber solution containing dissolved H_2S is oxidized with air to regenerate the solution. During the oxidation step, H_2S is oxidized to elemental sulfur. H_2S removal efficiency for the Stretford process is about 99 percent^{5/}. Total annual power generation cost is reported to be about 0.5 mill/Kwh, based on a 100 MW plant and an H_2S concentration of 220 ppm^{2/}.

A surface condenser is a requirement for the Stretford process so that direct contact of the cooling water and condensate is eliminated.

There are now between 50 and 60 Stretford units in successful operation in various gas-treating application. Although there are no units yet in commercial operation on geothermal facilities, the process has been selected for installation on Geyser Units 13, 14 and 15.

Jefferson Lake Process: The Jefferson Lake process involves a variation of the Claus process. Gases containing H_2S are reacted with SO_2 in a catalytic reactor to form sulfur and water. Part of the sulfur is oxidized to form SO_2 , which is then recycled back to the reactor.

The presence of moisture and CO_2 is detrimental to the H_2S - SO_2 reaction, since carbonyl sulfide can be formed as a side reaction.

The Jefferson Lake Process is currently under investigation for use on a 150 MW geothermal power plant at Cerro Prieto, Mexico. Economics of the process is believed to be highly dependent on the recovery of by-product sulfur.

Burner-Scrubber Process: In this process, the vent gases are incinerated and the combustion products scrubbed with water. Sulfur dioxide dissolved in the scrubbing liquid is returned to the condensate stream, dropping the pH in the condenser hotwell, thus causing more H_2S to be removed with the vent gases.

A full-scale prototype of the burner-scrubber concept was tested on the Geysers Unit 4. A maximum H_2S removal efficiency of 50 percent was achieved based on the inlet concentration^{2/} of H_2S ^{7/}.

A variation of the Burner-Scrubber process is the catalyst-scrubber process, developed by Union Oil Company. This process uses a catalyst to selectively oxidize H_2S to SO_2 . Since oxidation occurs without combustion, this process is potentially simpler and safer^{2/}. However, its efficiency is not expected to be greater than 50 percent. This process is projected to be installed on the Geysers 53 MW Units 5 and 6 sometime in 1978^{2/}.

Iron Catalyst Process: The iron catalyst (or Ferrifloc) system was developed by Pacific Gas and Electric for removal of H_2S from the steam condensate at power plants. It is presently in use at the Geysers geothermal field.

In this process, ferric sulfate is added to the cooling water/condensate stream, thus oxidizing H_2S contained in the aqueous phase. The noncondensable ejector gases are ducted to the cooling tower and H_2S is scrubbed by the falling water containing the ferric sulfate catalyst. Experience at the Geysers shows that H_2S in the cooling water/condensate is stripped as it passes the cooling tower. Therefore, the iron catalyst process must be applied to the cooling water upstream of the cooling tower.

Table 3. Control Technology for H_2S Removal from Cooling Water Condensate

Major Processes:

- * Iron Catalyst Process
- * Hydrogen Peroxide (H_2O_2) Process
- * Use of Ozone
- * Wackenroder Reaction

Other Processes:

- * Electrolytic Oxidation
- * Ion Exchange
- * Reverse Osmosis

Problems with this process include corrosion of equipment, plugging of filters, and disposal of toxic sludge. In spite of these problems, the process operates commercially with an efficiency of 90 to 92 percent. Total annual cost is reported to be 0.4 mill/Kwh for a 100 MW plant based on 220 ppm of H_2S .

H₂O₂ Process: H₂O₂ reacts with H₂S in an acidic or neutral aqueous solution (pH less than 8) to produce elemental sulfur and water. In alkaline solutions with pH greater than 8, the sulfide reacts with H₂O₂ to produce sulfate and water.

FMC Corporation has conducted laboratory experiments on oxidation of H₂S in cooling water/condensate samples taken from the Geysers power plant. Based on the experiments, the process is feasible. An H₂S removal efficiency of 88 percent was obtained in less than 3 min., when the initial H₂S concentration was 12.2 ppm^{2/}. No catalyst was used and the H₂O₂:H₂S weight ratio was 1.9^{2/}.

Ozone: Ozone has not been used to oxidize H₂S in the aqueous phase, but it has been shown to oxidize H₂S in the gaseous phase^{2/}. The feasibility of this process cannot be determined at the present time, due to lack of adequate reaction rate data.

Wackenroder Reaction: This reaction is the liquid phase equivalent of the Claus reaction, which uses SO₂ for the oxidation of H₂S to form sulfur and water.

Laboratory experiments conducted by Pacific Gas and Electric were apparently successful when SO₂ was injected into condensate/cooling water containing H₂S, but no published reports of this work are available.

Other Processes: Electrolytic oxidation, ion exchange and reverse osmosis are all applicable, in theory, for H₂S removal from cooling water/condensate. However, the economics of these processes makes them unattractive^{8/}.

Evaluation of Available H₂S Removal Processes

The available processes can be compared using a variety of factors. For this evaluation, the following factors were chosen:

- a. Process Availability
- b. Ease of Adaptability to Application
- c. Potential for H₂S Removal
- d. State of Development

Process Availability: As used here, this denotes whether a particular process has been demonstrated (D) or whether it is feasible merely from a conceptual standpoint or theory (C).

Ease of Adaptability: This criterion is used to determine if an H_2S removal process can be adopted for the geothermal application that is under consideration.

Potential for H_2S Removal: This denotes H_2S removal efficiency.

State of Development: This signifies whether a process has been demonstrated on a laboratory scale (L), pilot scale (P) or commercial scale (CM).

Cross-media Impacts: Secondary environmental problems such as release of secondary air pollutants, sludge disposal or wastewater treatment and disposal are implied in this category.

Operating Constraints: The need for high temperature, high pressure or corrosion resistant environments, and high energy requirements, if any, are included in this criterion.

Total Annual Power Cost: This includes capital, operating and maintenance costs and is based on a 100 MW plant. (Data used here are obtained from Reference 2.)

Figure 1 is an evaluation grid consisting of the above factors. From this figure, one can select the most promising H_2S removal processes by assigning priorities to each of the factors contained in the grid.

In this evaluation, the following factors were assigned top priority.

- a. The process had to be demonstrated as being feasible (i.e., D rating).
- b. H_2S removal efficiency of 80 percent or better.
- c. Minimum acceptable state of development was lab scale*.
- d. Annual power costs should be less than 10 mill/Kwh for 100 MW plant.
- e. Cross-media impacts should be minimal.

* Those processes that have been commercialized.

Figure 1. Evaluation Grid for Comparing H₂S Removal Processes

H ₂ S Removal Process	Process Availability (C or D)	Ease of Adaptability (+, -)	Potential for H ₂ S Removal	State of Development (L, P, CM)	Cross-Media Impacts	Operational Constraints
<u>Upstream Technology</u>						
EIC Process ^{a/}	D	+	97%	P	None	Not Known
Deuterium Process ^{a/}	D	+	90%	P	Not Known	Not Known
Solid Sorbent Process ^{a/}	D	+	Not Known	L	Not Known	Not Known
Dow Oxygenation Process ^{b/}	D	+	90-100%	L	SO ₂	Corrosive
<u>Vent Controls</u>						
Stretford Process	D	- ^{c/}	99%	P	None	Not Known
Jefferson Lake Process	D	-	Not Known	L	Not Known	Not Known
Burner-Scrubber Process	D	+	50%	P	SO ₂ , NO _x	Not Known
<u>Cooling Water/Condensate Controls</u>						
Iron Catalyst Process	D	+	90-92%	CM	Sludge Disposal	Corrosive
Hydrogen Peroxide Process	D	+	88%	L	Not Known	High Temperature
Ozone Process	C	Not Known	Not Known	Not Even L	Not Known	Not Known
Wackenroder Reaction	D	Not Known	Not Known	L	Not Known	Not Known
C - Concept, D - Demonstrated, L - Lab Scale, P - Pilot Scale, CM - Commercial						

^{a/} For vapor-dominated sources.

^{b/} For liquid-dominated sources.

^{c/} Requires surface contact condensers.

^{d/} Safety aspects may be an added problem.

- a. EIC Process
- b. Dow Process
- c. Deuterium Process

For Vent Controls:

- a. Stretford Process

For Cooling Water/Condensate:

- a. Iron Catalyst
- b. H_2O_2

3. CONCLUSIONS AND RECOMMENDATIONS

Based on the foregoing analysis, the most promising processes appear to be the EIC process, the Dow Oxygenation process, the Deuterium process, the Stretford process, the Iron Catalyst process and the H_2O_2 process.

Among the processes mentioned above, the Iron Catalyst process is already commercial. For the remaining processes, the following priority is recommended for further support and development.

- a. EIC
- b. Dow
- c. Stretford
- d. H_2O_2
- e. Deuterium

advantages of upstream removal of H_2S . The EIC process is also close to commercialization. For the same reason, the Stretford process is ranked third. The Deuterium process is ranked last because of the proprietary nature of the process and lack of reliable information.

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ABSTRACT

EIC Corporation, with support from the Department of Energy and Pacific Gas and Electric Company, has been engaged in the development of a process for the removal of hydrogen sulfide from geothermal steam.

The development effort has been carried out in a three phase program which includes fundamental studies at the laboratory scale to define the basic chemistry of the process and to obtain preliminary design data, an engineering design and development effort to demonstrate the applicability of the process on real geothermal steam and to develop the design of a demonstration plant, and the construction and operation of an integrated demonstration plant for the process at a 5 MW scale.

The process, which removes hydrogen sulfide at turbine upstream conditions, is based on the chemistry of the acid copper sulfate-hydrogen sulfide system. The essential steps in the process include contacting the steam with copper sulfate solutions, separating the reaction products to purge soluble impurities and to direct the precipitated copper sulfides to regeneration, and regeneration of copper sulfate for recycle.

In this paper, we will describe the development program which has been carried out and the current status of the demonstration plant. The experimental and analytical work which has been carried out and the preliminary process design criteria for the process will also be presented.

INTRODUCTION

Some years ago EIC Corporation became aware that the presence of hydrogen sulfide in geothermal steam could potentially constrain the development of this resource. The problem did not seem to be the subject of a large, organized research and development effort, probably because the resource, although locally important, is small by national terms. The utilities extracting power from geothermal steam were attempting to cope with the environmental problem by retrofitting pilot plants on to operating production plants. This is a difficult way to test and develop any new process even under the most favorable circumstances. EIC Corporation saw this problem as an area in which the company's skills in inorganic and physical chemistry, hydrometallurgy, and chemical process engineering could be brought effectively to bear. Therefore, we undertook a thorough review of the process requirements for hydrogen sulfide abatement from the point of view the fundamental chemistry

emphasized that the indicated distribution is only approximate; it is very difficult to make all the measurements required to close a material balance. Furthermore, one must be cognizant of the fact that the total steam composition and in particular its ammonia and carbon dioxide contents, must also be considered in attempting to predict the fate of hydrogen sulfide a priori. Nevertheless, it is clear that the hydrogen sulfide is widely distributed throughout all parts of the power cycle and is present in the condensate at even lower concentrations than in the inlet steam by virtue of the large flow of cooling tower water required. Therefore, in comparing the virtues of upstream and downstream abatement, one must balance the advantages of operation at near ambient temperature and pressure against the difficulties involved in dealing with very dilute streams.

Of course, surface condensers could be substituted for baremetric units at a significant increase in cost but an increase in concentration of at least an order of magnitude would be obtained. An alternate approach would be to maintain the condensate in such a state that the hydrogen sulfide would be driven into the noncondensable gases where they would be concentrated by approximately 2-3 orders of magnitude over their content in the incoming steam. Hydrogen sulfide would then be removed from these gases, after they had been pumped up to atmospheric pressure by the system ejectors, by conventional means. The key design problem is to balance the operating requirements of the turbine with the actions necessary to remove hydrogen sulfide from the condensate. This would be accomplished partially by running a hot air blower or restripping condensate and by providing for oversize removal channels in the condenser to minimize contact between inerts and condensate. However, the chemistry of the condensation process must also be considered: while the steam contains both acidic (hydrogen sulfide and carbon dioxide) and basic (ammonia) gases, the relative rates of mass transfer from the inerts into the condensate differ widely and the final pH of the condensate is critical in determining hydrogen sulfide distribution. At low pHs, hydrogen sulfide solubility is low and it may be expected to report to the noncondensable gases. But if the condensate pH is high, ≥ 8 , a significant amount of sulfide will be dissolved and would then have to be removed by an additional treatment step.

The partial pressure of hydrogen sulfide upstream of the turbine is approximately 2 orders of magnitude higher than it is at turbine exhaust conditions but the temperature is also substantially higher and the partial pressure of carbon dioxide is approximately 10 times as high as that of H_2S . These considerations severely limit the practical process options for upstream hydrogen sulfide removal by conventional methods. It was felt, however, that the process possibilities should be explored in detail since the important collateral benefits of reduced emissions during trip outs and possibly reduced corrosion and deposition of solids which might increase turbine reliability would provide significant economic incentives to support the development of the new technology.

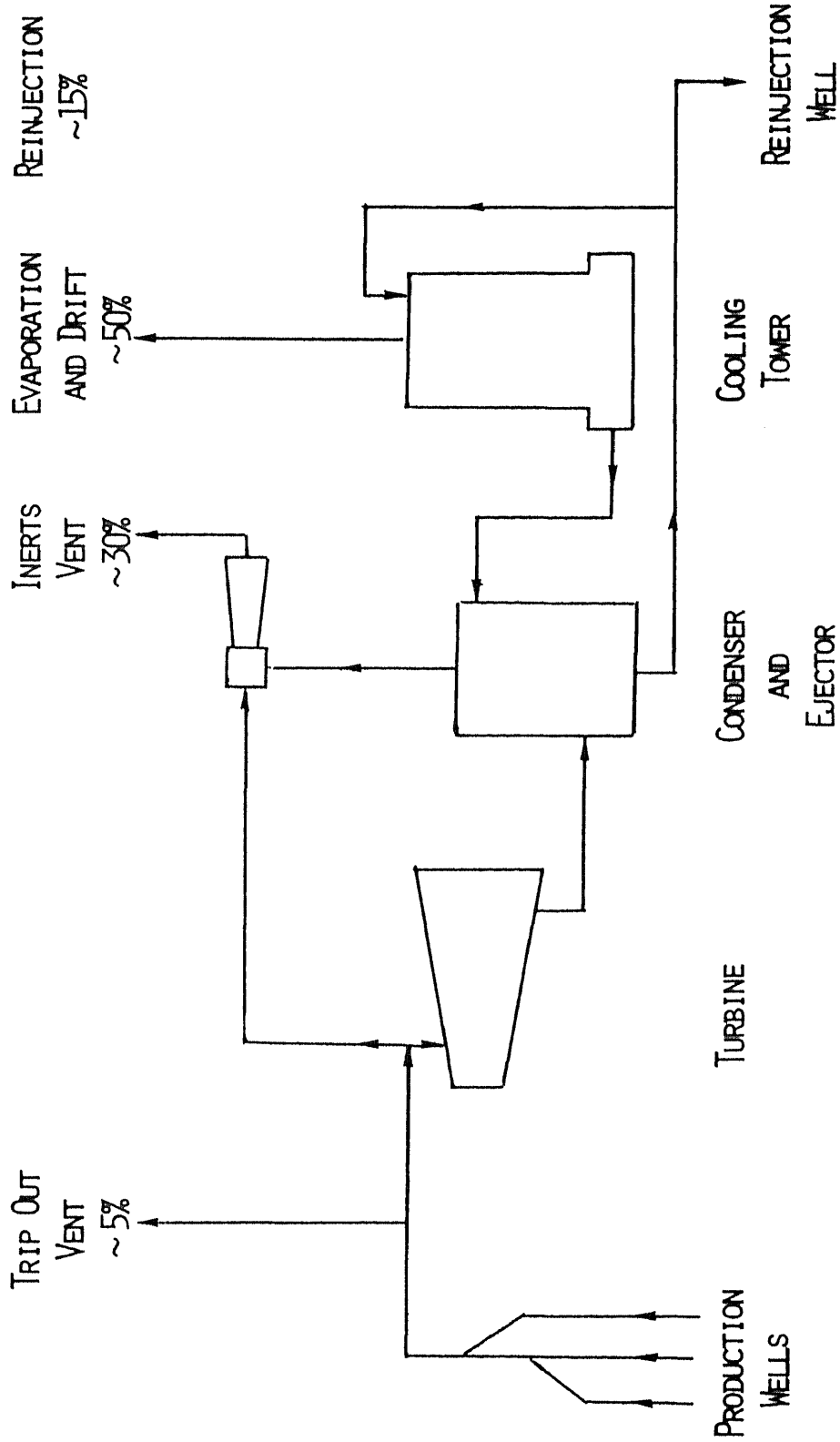


FIGURE 1. DISTRIBUTION OF SULFIDE EMISSIONS IN A CONVENTIONAL POWER PLANT.

tively remove hydrogen sulfide. The contacting and scrubbing agent must operate in such a way that degradation of steam quality and flow rate are acceptably low.

- Separation of the scrubbing agent from the cleaned steam with negligible losses of expensive reagents.
- Treatment of the scrubbing agent to recover the hydrogen sulfide removed from the geothermal steam and to regenerate the agent for cycle. Of course, if the scrubbing agent were cheap enough and could be disposed of in an environmentally acceptable manner, this step could be eliminated.
- Disposal of the hydrogen sulfide, or of reaction products of the hydrogen sulfide, in an economical and environmentally acceptable manner.
- Purging and disposal of other impurities scrubbed from the steam during the hydrogen sulfide removal step.

Important process objectives would be to obtain a very high degree of hydrogen sulfide removal, to concentrate the sulfide very significantly in order to reduce the size of subsequent material handling steps, to avoid production of unwanted byproducts or the introduction of still other objectionable materials to the environment, and to develop a process which would not impose undue operating problems or complexity in a plant whose prime objective is the generation of inexpensive power.

Our initial investigations focused on the search for an inexpensive scrubbing agent based on physical sorption. Such agents have been used in conventional processes, but we know of none which is suitable at a temperature of 175°C and in the presence of 9 atmospheres water partial pressure. The weak chemical bonds which are formed in these systems would not allow attainment of sufficiently low equilibrium hydrogen sulfide partial pressure at reasonable concentrations. Thus, we would be forced to accept either low removal efficiencies or be faced with processing very large flow rates of material in the regeneration step. Furthermore, none of the reagents appeared to be selective enough for hydrogen sulfide in the presence of still high partial pressures of carbon dioxide, and it was difficult to see how an economically viable process could be evolved if it of necessity removed or most of the carbon dioxide from the steam as well as hydrogen sulfide. We became convinced that physical sorption would not be a suitable approach for upstream abatement and redirected our efforts towards a review of a chemical system.

A review of the thermodynamics of sulfide-sulfate-water systems

For example, the standard free energy of reaction between aqueous copper sulfate and hydrogen sulfide at 175°C is -17.9 kcal/g mole. The high negative value indicates that the reaction goes sensibly to completion at any reasonable pH, so that near quantitative hydrogen sulfide removal could be obtained. Furthermore, the product of the reaction, copper sulfide, is essentially insoluble in the scrub solution under normal process conditions and so can be separated easily for regeneration of copper sulfate for recycle in a closed loop. We also recognized that the second reaction product, aqueous sulfuric acid, would reduce the pH of the scrub solution and would therefore be effective in removing ammonia from the steam as well. The simultaneous removal of hydrogen sulfide and ammonia, with subsequent regeneration of precipitated sulfide, serves as the basis for the copper sulfate process as summarized below.

Table 1

Process Concept for the Removal of Hydrogen Sulfide from
Geothermal Steam using Copper Sulfate Solutions

$\text{H}_2\text{S}(\text{g}) + \text{CuSO}_4(\text{aq})$	\rightarrow	$\text{CuS}(\text{s}) + \text{H}_2\text{SO}_4(\text{aq})$	Concentration
$\text{CuS}(\text{s}) + 2\text{O}_2(\text{g})$	\rightarrow	$\text{CuSO}_4(\text{aq})$	Regeneration
$2\text{NH}_3(\text{g}) + \text{H}_2\text{SO}_4(\text{aq})$	\rightarrow	$(\text{NH}_4)_2\text{SO}_4(\text{aq})$	Neutralization
<hr/>			
$\text{H}_2\text{S}(\text{g}) + 2\text{NH}_3(\text{g}) + 2\text{O}_2(\text{g})$	\rightarrow	$(\text{NH}_4)_2\text{SO}_4(\text{aq})$	Abatement

The sequence of operations involved in an integrated process is shown schematically in Figure 2.

While the basic chemistry of the process was well known, it was clear that a substantial development effort would be required to demonstrate that a technically and economically viable process based on this chemistry could be evolved. Of particular concern were the kinetics of both the scrubbing and regeneration reactions. It had to be demonstrated that hydrogen sulfide partial pressures could be reduced to the order of 10^{-5} atmospheres within a short contact time and that the sulfide material precipitated in the reaction could be quantitatively regenerated under reasonable process conditions. Concern was also expressed over the nature of the precipitates which would be formed since, in classical laboratory analytical procedures, colloidal sulfides are known to form which make the liquid solid separation steps difficult. Accordingly, EIC proposed to carry out, in stages, a three-phased program to develop and demonstrate the process concept as summarized below.

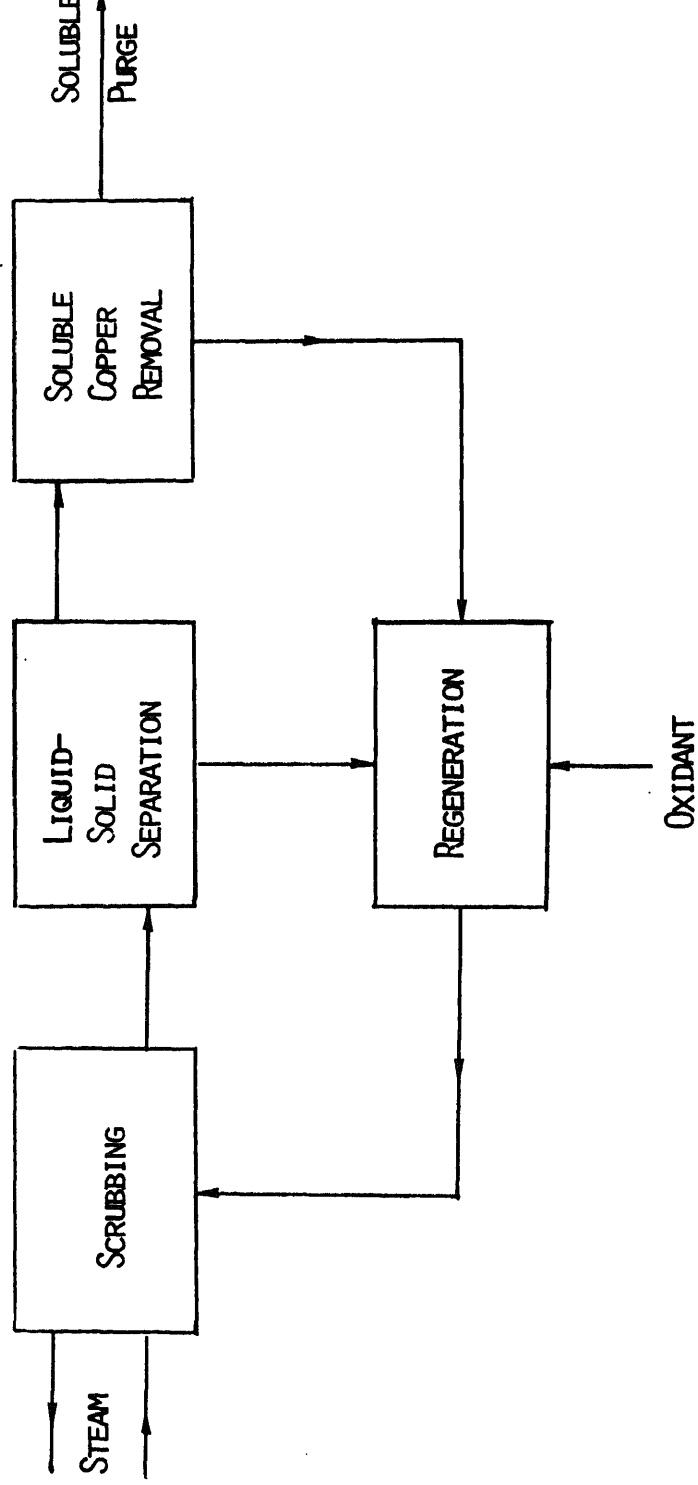


FIGURE 2. SEQUENCE OF OPERATIONS IN AN INTEGRATED PROCESS.

<u>Phase</u>	<u>Activity</u>	<u>Duration</u>
Phase 1	Laboratory Process Development	1 year
Phase 2	Demonstration Plant Design and Process Evaluation	1½ years
Phase 3	Demonstration Plant Construction and Operation	1½ years

This work, supported by the Department of Energy and Pacific Gas and Electric Company, will be summarized in the following sections.

LABORATORY PROCESS DEVELOPMENT

The details of the laboratory process development effort have been presented elsewhere and only the highlights will be summarized here.^{1,2} This phase of the development effort, lasting approximately 1 year, provided the basic data, at a laboratory scale, to confirm that the proposed process concept was indeed sound.

Scrubbing tests were carried out in 2" and 4" diameter columns on "simulated" geothermal steam, obtained by metering known amounts of hydrogen sulfide and other gases into boiler steam, which was fed to the scrubbing apparatus. Steam flow rates were of the order of 100-200 lbs/hr, and a variety of internals styles were evaluated in the scrubbing columns. It was found that the system was surface active; flooding of packed internals occurred at vapor velocities far lower than expected and the froth densities observed on trayed internals were surprisingly low. It was also shown however, that with proper tray design, it would be possible to obtain both high removal efficiencies and good operability at reasonable vapor velocities without any apparent tendency for fouling of the tray or scrubber surfaces.

A wide range of scrubber hydraulic conditions and solution compositions were tested in order to determine the effect on removal rates and scrubbing efficiency for both hydrogen sulfide and ammonia. It was found that hydrogen sulfide removal efficiencies were independent of solution copper content above approximately 1 gram per liter, but that both hydrogen sulfide and ammonia removal efficiencies were strongly influenced by the scrub solution pH. At pHs (measured at room temperature) below about 1, hydrogen sulfide removal efficiencies decreased significantly while ammonia removal efficiencies increased as expected. Above a pH of approximately 2, ammonia removal

¹First Annual Report, Contract No. EY-76-C-02-2730.*000. Control of Hydrogen Sulfide Emissions from Geothermal Power Plants.

²Hydrogen Sulfide Removal from Geothermal Steam, F. C. Brown, W. W. Harvey and

It has been repeatedly shown that the precipitated sulfides which are formed under upstream scrubbing conditions, rather than being colloidal, in fact rapidly agglomerate to form centimeter size aggregates and settle rapidly. Scanning electron microscopy of the aggregates reveal that the ultimate particle size is of the order of a few microns. Thus, we anticipated that the enormous surface area per unit mass would result in very favorable regeneration kinetics.

It was indeed found that the sulfide solids could be regenerated quantitatively and rapidly by either roasting under rather mild conditions or by hydrothermal leaching with air or oxygen. The chemistry of both the scrubbing and the regeneration reactions is actually somewhat more complicated than indicated in the previous table. Under scrubbing conditions, the cupric sulfide formed in the initial precipitation reaction is subject to alteration with the formation of cuprous sulfide, elemental sulfur, and sulfate. The solids produced are actually a mixture of cuprous and cupric sulfides and, being nonstoichiometric, are inherently very reactive.

Thus, we had demonstrated at the laboratory scale that each of the key process steps - scrubbing, liquid/solid separation, and regeneration - could be carried out in equipment of conventional design with the desired process criteria of high removal efficiencies and quantitative regeneration being met under practical conditions. A preliminary economic evaluation was sufficiently encouraging that the second phase of the development effort was begun immediately.

DESIGN OF THE DEMONSTRATION PLANT AND PROCESS EVALUATION

It was recognized that, no matter how convincing a laboratory demonstration might be, it would be necessary at some point to provide for a test at a reasonable scale on actual geothermal steam. The main objective of the second phase in this development effort was to obtain the information necessary to support the design of an appropriate demonstration plant. The program which was developed to meet these objectives included a series of laboratory support and process engineering studies as well as the detailed project and process engineering work required as summarized below.

Our intent in structuring the program in this way was first to carry out laboratory support studies in order to obtain specific data for the design of the demonstration plant and then to carry out additional work aimed at gathering supplementary data. This would permit us to optimize the process design and to scope the range of process variables which ought to be tested during operation of the demonstration plant.

Corrosion studies on austenitic stainless steels under expected scrubber operating conditions was the first task undertaken. Limited testing in the laboratory development phase had shown that stainless steels might be

Demonstration Plant Design Program

Laboratory Support Studies

Corrosion Studies on Austenitic Stainless Steels

Leach Regeneration Studies

Filter Leaf Filtration Studies

Analytical Technique Development

Process Engineering Studies

Materials Testing

Roast Regeneration Studies

Liquid/Solid Separation Studies

Scrubber Configuration Studies

Project and Process Engineering

Program Definition

Eight Inch Column Design and Operation

Preliminary Project/Process Engineering

Detailed Project/Process Engineering

Test Plan Preparation

Optimization and Economics Studies

acceptable materials of construction, but that the results were erratic. In these studies, it was found that if the scrub solution could be maintained in an oxidizing condition by the presence of a sufficient concentration of cupric ion and that if the solutions acidity were controlled, austenitic stainless steels would be passivated. It was also found however, that these materials would be subject to attack by crevice corrosion, probably due to slow local depletion of the solution copper content with attendant loss of passivation. The corrosion resistance of the materials tested under simulated scrubber conditions is:

Ti >> EB26-1 > C20Cb3 ~ UHB904L > T330 ~ T310 > T304 ~ T316

Considerations of cost and availability led us to select C20Cb3 as the material of construction for the prototype scrubber, with titanium being considered a backup material.

from solids produced in field trials at the Geysers. Initially, these tests showed that near quantitative removal (>99% regeneration) could be obtained under modest processing conditions viz. oxygen partial pressure 50 psi, temperature 135°C, with three hour residence time. Data from a typical run are shown in Figure 3, where the data have been linearized by plotting according to the parameters derived from a shrinking core model. Observed activation energies are in the range of 5 kcal/g mole indicating that the limiting rate is diffusion rather than kinetically controlled.

Filter leaf filtration studies confirmed the observed rapid filtration rate and were consistent with properties of highly aggregated solids. However, the cake densities which were formed were so low, of the order of 20% solids, that a continuous filtration step would be dominated by the volumetric capacity of the filtering device and not the filter area. This consideration led us to revise the specifications for the liquid/solid separation step and the design criteria now call for the use of a continuous decanter. Required underflow densities can be obtained with detention times of less than 2 minutes, and acceptable overflow clarities are obtained at upflow velocities of 30 ft/hr.

The process control concept which has been evolved requires that the scrub solution be refreshed with makeup copper sulfate to maintain its copper content at the desired level and to control the build up of acidity. This required the development of online analytical techniques for the measurement of dissolved copper and pH in a highly reliable way. A variety of techniques were investigated and we determined that an online photometric analyzer for copper and a pH analyzer with an acid sulfate reference system would be suitable for field use. In fact, the instruments tested in our laboratory will be incorporated in the control instrumentation tested in the demonstration plant.

The material testing studies focused on evaluating alternative materials suitable for use under conditions external to the scrubber. It was shown that type 304 stainless steel would be suitable for any process application at temperatures below 125°C, but that composite materials such as Derakane would be suitable for temperatures below approximately 50°C, and for short times up to 110°C.

The roast regeneration studies confirmed our initial experiments indicating the acceptability of this technique. However, since enriched solids are produced, roasting of sulfides in the absence of an external source of sulfate will produce a mixture of copper oxides and copper sulfate. Some fundamental kinetic work under roast regeneration conditions are available to support the design of suitable equipment, but the optimization and economic studies do not indicate that this would be a favorable approach.

Additional liquid solids separation work was carried out to support the design of centrifuges and continuous filters but, as is the case with regeneration by roasting, these alternatives do not appear to be favored economically.

An additional series of small

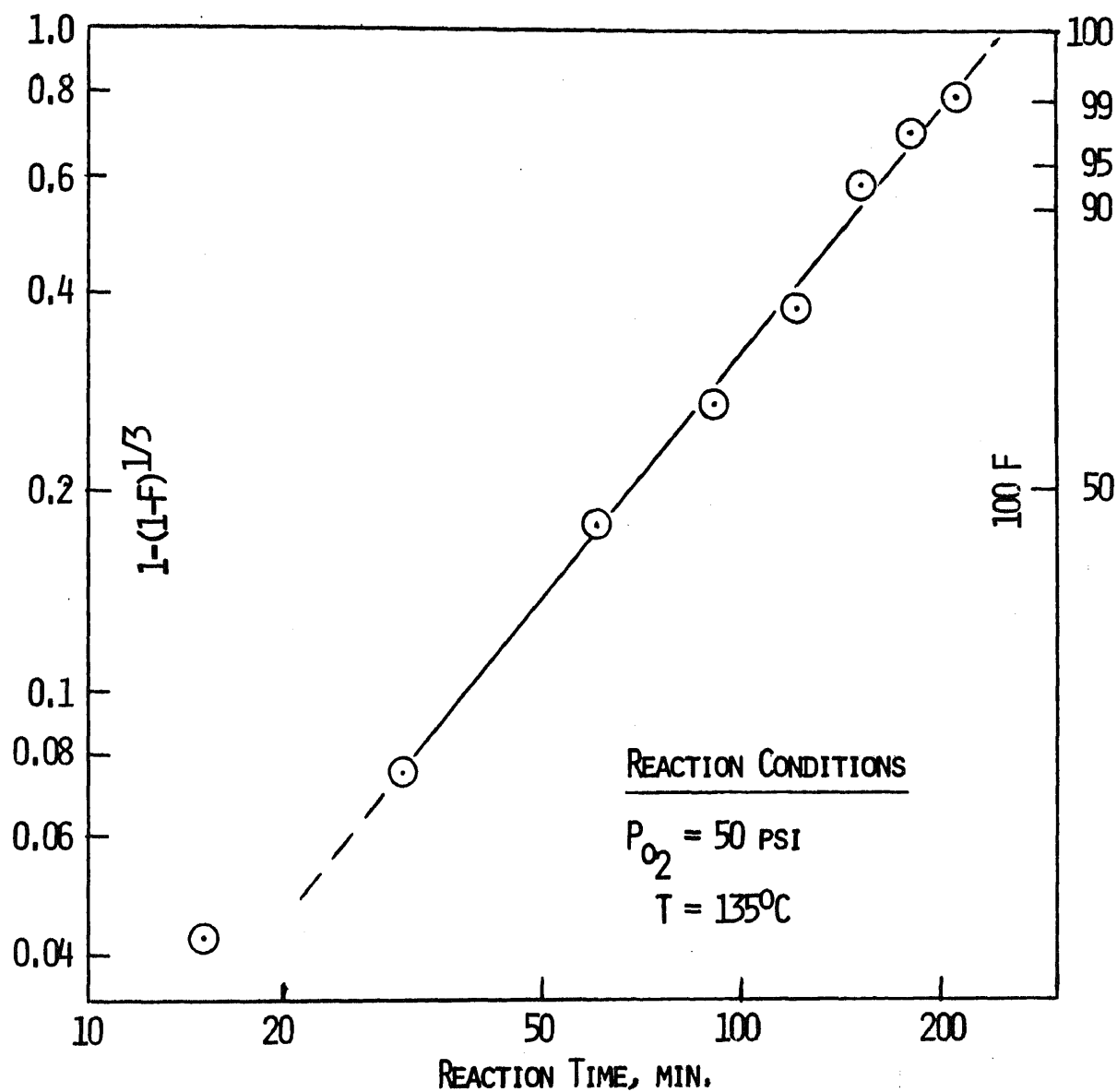


FIGURE 3. FRACTION SOLIDS REACTED, F , VS. REACTION TIME.

were tested as well as a simple, single stage venturi. A single crossflow sieve tray installed in a conventionally designed scrubbing tower would be the optimum type of contactor when high degrees of hydrogen sulfide removal are required. If lower degrees of hydrogen sulfide removal, of the order of 90%, and somewhat higher pressure drops, up to 5 psi, are acceptable, a single stage venturi contactor would be attractive.

The aforementioned laboratory support and process engineering studies and the operation of an 8" scrubber at The Geysers provided the necessary data to support detailed process and project engineering. The 8" field scrubbing unit, shown in Figure 4, was designed based on criteria derived from the laboratory tests. The objectives of designing and operating this unit were to confirm the preliminary criteria and to ascertain whether any unanticipated problems would arise from the scrubbing of "real" steam. Fortunately, no major operating problems were encountered and near quantitative removal of hydrogen sulfide was obtained as shown in Figure 5. High degrees of ammonia and boric acid removal were also obtained and the solids produced from "real" geothermal steam were as well behaved as those produced in the laboratory. The fabled "Geysers Gremlin" made only one appearance during the third hour of the test when our analyst was on a lunch break and the scrub solution copper content dropped to 0.5g/l.

The laboratory, field, and analytical studies confirmed the preliminary economic evaluation which showed the EIC process could be technically and economically viable for the upstream removal of hydrogen sulfide from geothermal steam. Accordingly, a decision was made to proceed with the final phase of the development effort, the construction and operation of a demonstration plant.

DEMONSTRATION PLANT CONSTRUCTION AND OPERATION

Work on this phase of the development program has been underway for approximately 6 months. Major items of equipment have been purchased and are being fabricated. Auxiliary items including pumps, instrumentation, and controls are being assembled, and site work has begun with excavation and foundation work completed. The program schedule calls for equipment installation to begin in January 1979 and be completed by April.

The process flow diagram for the demonstration plant is presented in Figure 6. All major steps in the process will be demonstrated in equipment of scaleable design. The scrubbing tower, 6' in diameter and approximately 30' high, and auxiliary equipment have been sized to treat 100,000 lb/hr of geothermal steam. The steam will be withdrawn from the main feeding Unit No. 7 at The Geysers, and cleaned steam will be returned to the turbine. Energy recovery will be effected in heat exchangers of conventional design, and the decanter used for liquid solid separation will be 10" in diameter. While scrubbing and liquid solid separation will be carried out continuously, regeneration will be carried out batch wise on one shift per day, in a 3500 gallon agitated pressure reactor. The reactor has been designed to be compatible with use of either compressed air or pure oxygen as an oxidant. Surge tankage with the capacity to hold one days flow of purge slurry or makeup copper sulfate has been provided.

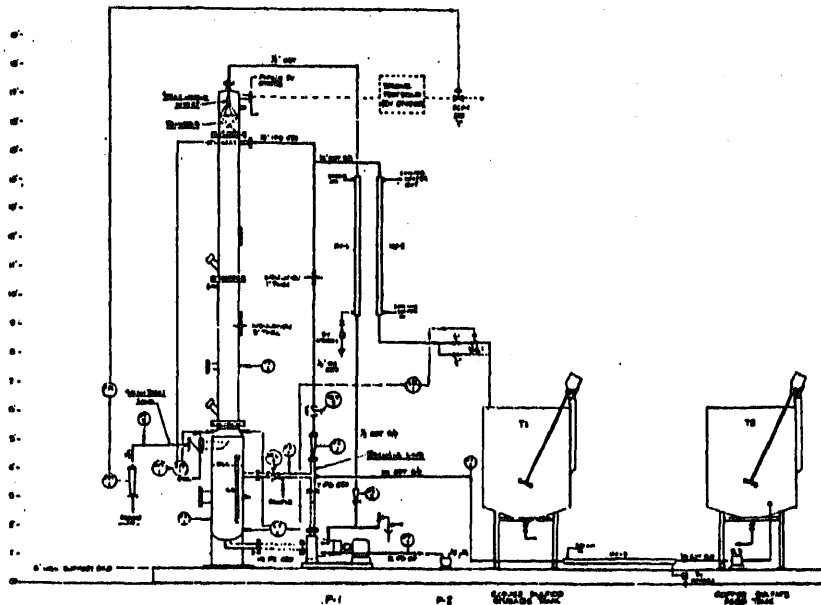


FIGURE 4. EIGHT INCH SCRUBBING UNIT.

products and soluble materials scrubbed from the steam, will be continuously and decopperized intermittently and mixed with Unit No. 7 cooling tower blow down for disposal. Provisions have been made to add sulfuric acid and ammonia to the process to vary the scrub solution pH as required and to add makeup copper to offset losses in the soluble purge stream. A plot plan for the installation is shown in Figure 7. All major process pumps, controllers, and interconnecting piping and auxiliary equipment will be shop assembled and mounted on the five skids indicated in the drawing.

A six month test campaign consisting of four major phases, summarized in the Table below is planned.

Table 4

Field Test Campaign for the Demonstration
of the Copper Sulfate Process

Water Testing and Operating Training

Open Circuit Scrubbing and Regeneration Testing

Short Term, Closed Circuit Testing

Long Term, Closed Circuit Testing

Immediately following mechanical integrity testing, all operations in the process will be carried out with steam and water as the working fluids. The objective of this phase of operations is to calibrate the process instruments and controls and establish a clean equipment reference state which will be used to determine the rate of fouling should it occur. In addition, the operating crew will gain experience with the system over a wide range of conditions under circumstances in which operating hazards are minimized.

In the second phase, a series of one or two day runs will be made in which each operation - that is scrubbing, liquid/solid separation, and regeneration - will be tested without considerations of operating the system in a closed loop with recycle of regenerated material. Not only will this ease operating problems in the initial stages of the campaign but it will permit the effects of discretely different operating conditions in one step - scrub solution copper content for example - on subsequent operations - such as liquid solid separation or regeneration - to be determined.

In the third phase of the test operations, the process will be operated in an integrated fashion, but operating conditions will be varied over the widest possible range. Attempts will be made to determine the limits of system stability, the response of the system to upsets, and scrubbing and regeneration efficiencies under conditions which are not "normal" for the material balance and operating conditions specific to the process.

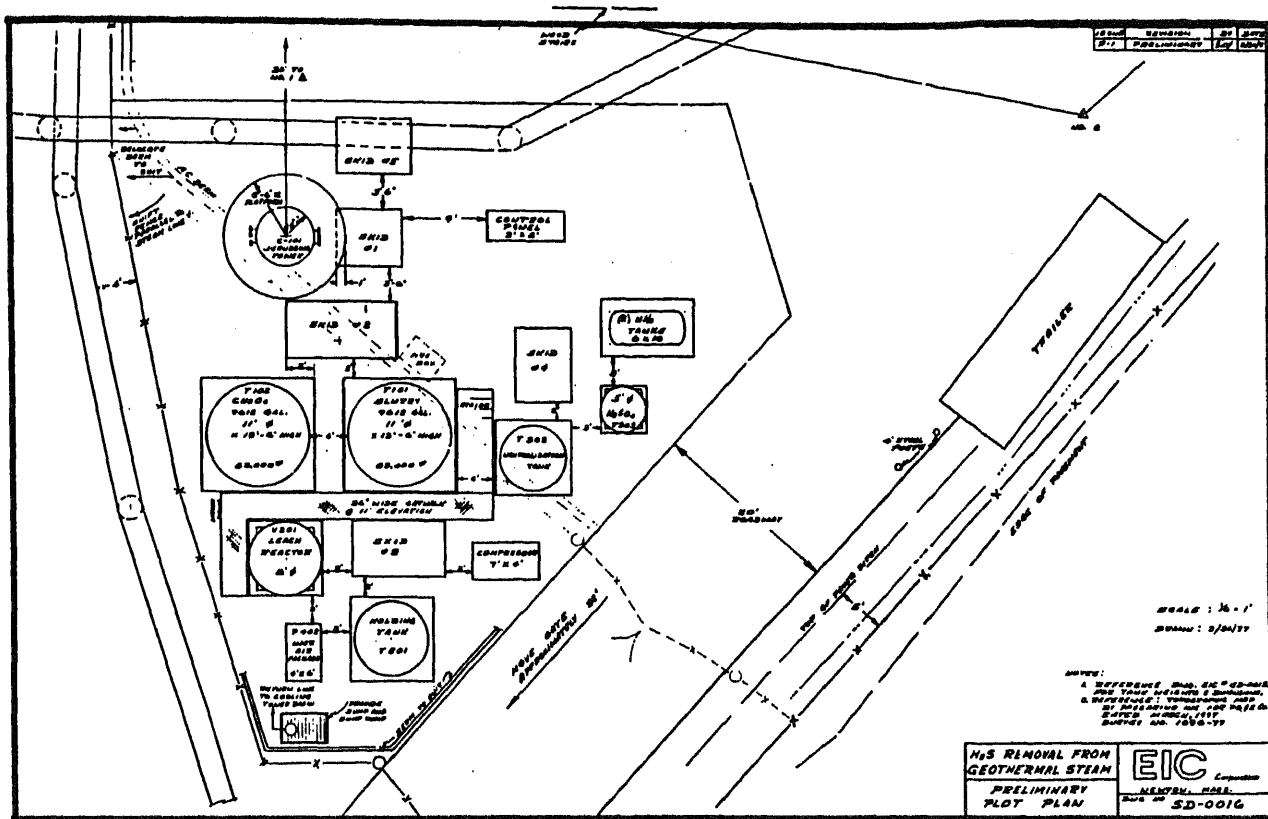


FIGURE 7. PLOT PLAN FOR 5 MW DEMONSTRATION PLANT.

bility demonstration and as an attempt to bring the system to a steady state for a long enough period to insure that changes which occur only slowly are recognized.

Our schedule calls for the final campaign to be concluded in October. A report of test will be written in January, 1980, following inspection of the plant and decommissioning. This report will update the design criteria for the process and will serve as the basis for recommendations for the process and mechanical designs for a commercial scale, 55 MW plant.

1. INTRODUCTION

Development of many geothermal energy sources is hindered because geothermal fluids contain impurities. One such impurity, hydrogen sulfide (H_2S), is present in steam from most geothermal sources. Concentrations of H_2S as high as 1,600 ppm have been reported at the Geysers.⁽¹⁾ However, the concentration of H_2S in geothermal steam usually ranges from 60 to 1,000 ppm. The direct use of geothermal steam containing H_2S for power generation has been reported⁽²⁾ to be both corrosive to the power generation-transmission equipment and offensive to the environment.

The H_2S problem in using geothermal steam for power generation has been illustrated by Bowen⁽³⁾ in the following situation. A power plant with a capacity of 1,000 MWe requires 430 million pounds of steam per day. If the H_2S concentration in the steam is 225 ppm (the average H_2S concentration in steam produced at the Geysers) a total of 48.4 tons of H_2S per day is carried by the steam to the surface. If 30 percent of the H_2S is returned to the reservoir with the steam condensate, the total H_2S released to the atmosphere would be 33.9 tons per day. An H_2S release of this magnitude could lead to atmospheric concentrations such that corrosion of power generation and transmission equipment and environmental impacts could occur.

Since early 1975, Pacific Northwest Laboratory (PNL) under sponsorship of DOE (then ERDA) has been developing processes to remove H_2S from geothermal steam. The following criteria were established for such removal processes:

- They should be applicable upstream of the power generation equipment to reduce H_2S corrosion problems.
- They should cause minimum degradation of steam quality.
- They should produce useful or environmentally innocuous byproducts.
- They should be inexpensive and simple to operate.

Two different processes have been investigated at PNL:

- (1) sorption (both chemical and physical) of H_2S by solid sorbents, and
- (2) oxidation of H_2S in the presence of oxygen and catalysts.

In the first process, zinc oxide pellets were found to react with and remove H_2S from geothermal steam. However, it was also found that the regeneration of the spent zinc oxide (zinc sulfide) was technically infeasible

(a) Pacific Northwest Laboratory is operated for the U.S. Department of Energy (DOE) by Battelle Memorial Institute.

due to the preferential formation of zinc sulfate in the regeneration cycle. Consequently, the use of this sorption process to remove H_2S from geothermal steam has been abandoned.

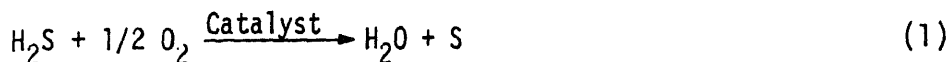
In the second process, H_2S in geothermal steam was catalytically oxidized with oxygen to form sulfur and water. The catalyst employed was activated carbon. The sulfur was recovered from the spent catalyst as elemental sulfur. To date, we have removed H_2S from a simulated geothermal steam and recovered sulfur from the spent catalyst in our laboratory. This paper discusses the results obtained from experiments performed at PNL and presents a conceptual design of the process. Finally, advantages and problems of the catalytic oxidation process will be discussed.

2. REMOVAL OF H_2S BY CATALYTIC OXIDATION

The catalytic oxidation process and bench-scale experiments are described in the following paragraphs.

PROCESS DESCRIPTION

The removal of H_2S from geothermal steam by catalytic oxidation is a spin-off idea from the study of the sorption of H_2S by solid sorbents described previously. We found that H_2S could be catalytically oxidized to sulfur and water by the following reaction:



One product of the reaction is water, which is also the main constituent of geothermal steam. It therefore tends to give the erroneous concept that the use of the oxidation reaction for the removal of H_2S from geothermal steam will be infeasible. However, a simple thermodynamic calculation reveals that the oxidation reaction will proceed even under the geothermal conditions. The heat of reaction (at $25^\circ C$) is -52.98 Kcal/g-mole meaning that the reaction is an exothermic reaction. The free energy change of reaction is -46.74 Kcal/g-mole (at $25^\circ C$). The equilibrium constant defined in equation (2) is 1.92×10^{34} at $25^\circ C$ and 1.87×10^{21} at $175^\circ C$:

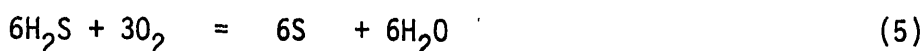
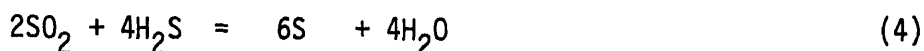
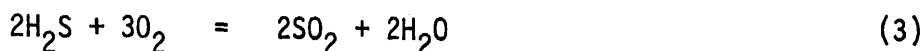
$$K_p = \frac{[p_{H_2O}]}{[p_{H_2S}] [p_{O_2}]^{1/2}} \quad (2)$$

where p_i is the partial pressure of the i^{th} component.

With this large equilibrium constant, at the temperature of the typical geothermal steam ($175^\circ C$) Reaction (1) should thermodynamically proceed from left to right. Based on typical geothermal steam conditions (225 ppm of H_2S) and with the stoichiometric amount of oxygen, more than 99.99 percent of H_2S

reaction rate and to accomplish a complete (or near complete) removal of H_2S by a reasonable size of reactor, a catalyst is required. The use of catalytic oxidation to remove H_2S from gas streams is an old process.⁽⁴⁾ For example, use of iron sponge and activated carbon box processes to remove H_2S from natural gas, manufactured gas, and coke-oven gas was commercially practical in the past. However, application of such processes to remove H_2S from geothermal steam containing more than 99 percent water vapor has not been practiced.

Besides the main reaction, side-reactions also take place in the oxidation system. The side-reactions are:



The SO_2 formed in Reaction (3) can be further oxidized to SO_3 according to the following reaction:

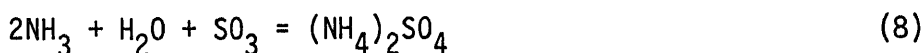


In the presence of metal oxides, present in some of the catalysts used, SO_3 is further converted to MSO_4 as shown in Reaction (7):



where MO and MSO_4 represent metal oxide and metal sulfate respectively.

Ammonia, as one constituent of the noncondensable gases in geothermal steam, can also react with SO_3 to form $(NH_4)_2SO_4$ according to Reaction (8):



In the catalytic oxidation process steam from geothermal wells is introduced to a reactor packed with a suitable catalyst. In the presence of the catalyst, the H_2S in the geothermal steam reacts with oxygen as shown in Reaction (1). The steam, after treatment, leaves the reactor for power generation. Sulfur produced in the reaction deposits on the surface of the catalyst and stays in the reactor. Because sulfur accumulates on the catalyst, the activity of the catalyst decreases gradually. When the H_2S concentration in the treated steam reaches a maximum allowable concentration, regeneration of the inactive carbon becomes necessary. Regeneration of the spent catalyst is accomplished by a solvent extraction process. Elemental sulfur is recovered from the extracted solution and the regenerated catalyst with or without a catalyst re-activation process is ready for the next run of H_2S removal. A block diagram of the catalytic oxidation process for the removal of H_2S from geothermal steam is shown in Figure 1.

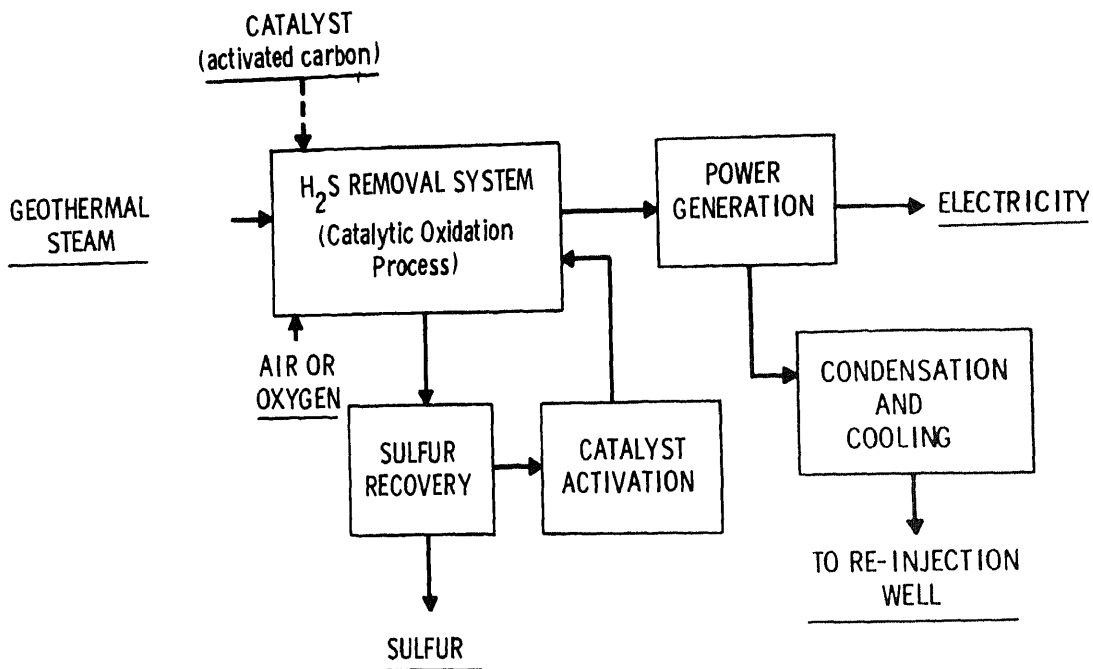


FIGURE 1. General Flow Diagram of the Proposed Catalytic Oxidation Process for H_2S Removal from Geothermal Steam

Water from a water supply is fed to the steam generator by a positive-displacement pump. Steam from the generator goes to the steam superheater where it is heated to the desired superheated condition. The temperature of the superheated steam is controlled by a variac connected to a heater in the superheater. Before entering the reactor, steam is mixed with noncondensable gases to form a simulated geothermal steam. The noncondensable gases studied include H_2S , CO_2 , CH_4 , H_2 , NH_3 , and N_2 .

The simulated geothermal steam and oxygen are then introduced to a catalyst packed reactor where the oxidation reaction, Reaction (1), takes place. The treated steam - gas mixture leaves the reactor and passes through a back-pressure regulator. Steam from the regulator, after being reduced to one atmosphere, is condensed, and the condensate is collected in a gas-liquid separator. The un-reacted noncondensable gases (such as N_2 , CO_2 , CH_4 , H_2 , and O_2) are separated from the condensate in the liquid-gas separator and flow to a wet testmeter where the total volume of un-reacted noncondensable gases is measured. The effluent of the wet testmeter is vented to the atmosphere through the building ventilation system. Gas samples are taken from the inlet and outlet of the reactor.

3. RESULTS OF BENCH SCALE EXPERIMENTS

The feasibility of the catalytic oxidation process for the removal of H_2S from geothermal steam has been studied at PNL in series of predesigned experiments carried out in the bench scale apparatus described in the previous section. A simulated geothermal steam, prepared by mixing steam with various noncondensable gases such as H_2S , CO_2 , H_2 , CH_4 , NH_3 , and N_2 , was used. Early in the study, H_2S was the only noncondensable gas used out of convenience. Although we intended to examine a variety of catalysts in the study, our efforts were concentrated in the use of different brands of activated carbon only. Reasons for using activated carbon as the catalyst included:

- Literature showed that activated carbon had been used in the oxidation process for removal of H_2S from different gas streams. (4,5,6,7)
- Activated carbon is readily available and relatively inexpensive.

The amount of activated carbon used in each of our experiments was 80 grams and the oxygen required for the reaction was supplied as air. The following are highlights of results obtained from our laboratory experiments.

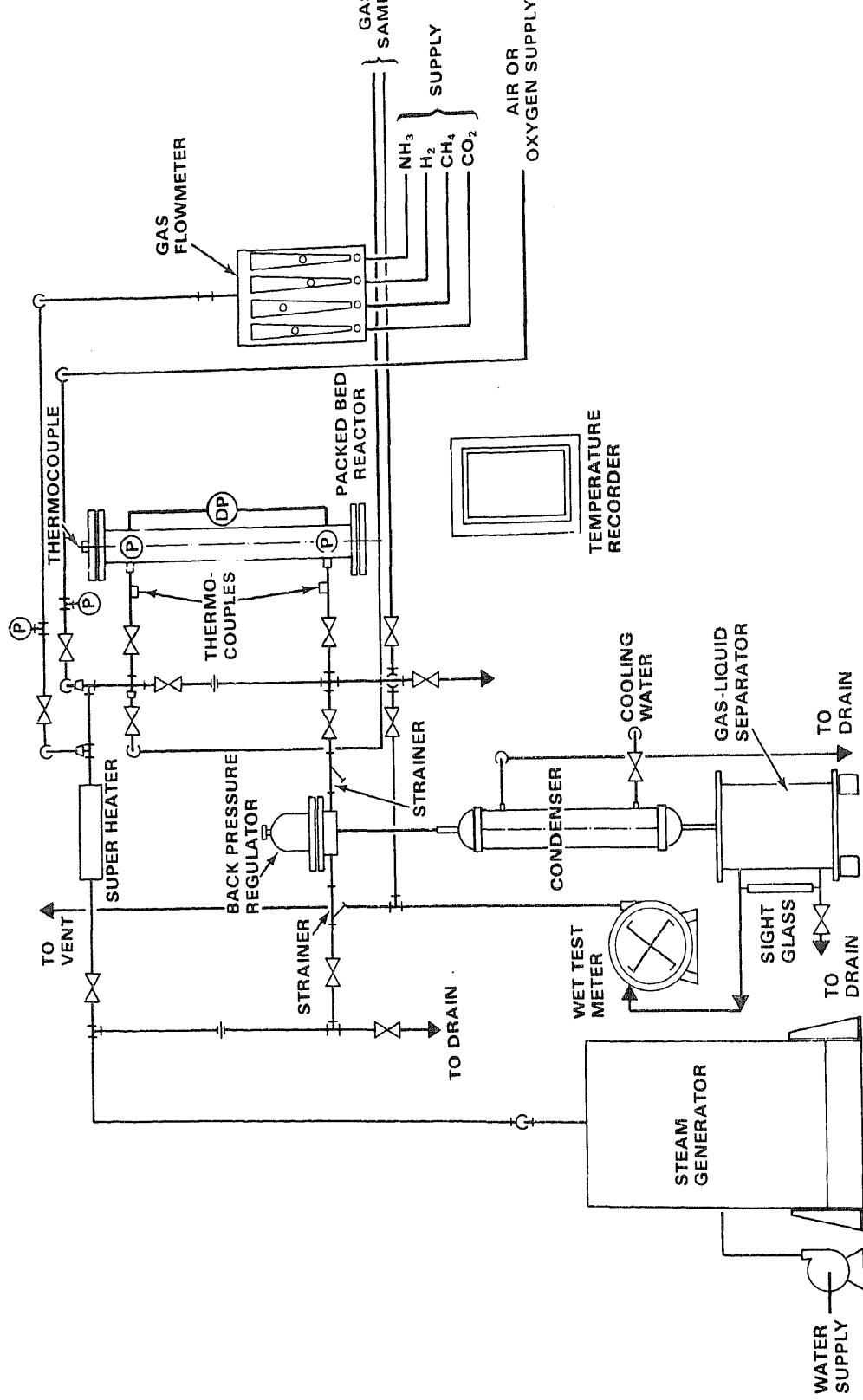


FIGURE 2. Bench Scale H₂S Removal Testing Unit

substantially less than 1 ppm can be easily accomplished. However, when the catalyst is fouled with sulfur as a result of reaction, the catalyst activity decreases and the outlet concentration of H_2S increases gradually. In this study, the breakthrough time is defined as the time required for the outlet H_2S concentration to reach 10 percent of that at the inlet. In most cases the breakthrough occurred after 13 hours of reactor operation. In one case we were able to operate the reactor for 27.5 hours. Results of some typical runs are shown in Table 1.

UPPER AND LOWER LIMITS OF OPERATING VARIABLES

Our experiments have shown that the catalytic oxidation process effectively removes H_2S from geothermal steam only when the steam is in a superheated condition. The effectiveness of the oxidation process diminishes as the temperature and pressure of steam approach the saturated condition. When the temperature of steam or the reactor is higher than $235^\circ C$, the entrainment of sulfur from the catalyst bed becomes significant. Therefore, to have an effective H_2S removal system, the reactor must be operated a few degrees higher than the saturated temperature of the steam and lower than $235^\circ C$. Also, under typical geothermal steam conditions, the pressure of the reaction system does not affect the H_2S removal capability of the oxidation process.

PRESSURE DROP OF STEAM ACROSS THE REACTOR PACKED WITH CATALYST

The pressure drop of steam across the steam treatment unit affects the amount of total power which can be produced. The higher the pressure drop the greater the energy loss that will occur. In our laboratory it was found that the pressure drop of steam across the catalyst bed follows Ergun's⁽⁸⁾ correlation as in Equation (9) quite well.

$$\frac{\Delta p \rho g_c}{G_o^2} \frac{D_p}{L} \frac{\epsilon^3}{1-\epsilon} = 150 \frac{1-\epsilon}{D_p G_o / \mu} + 1.75 \quad (9)$$

For a pilot plant, Equation (9) can be used to predict the pressure drop within an accuracy of one order of magnitude. The pressure drop is about 5 psi and 1 psi for carbon particle of 12x30 mesh and 4x10 mesh respectively, with a bed height of 11 in. and a steam rate of $22 \text{ g/cm}^2/\text{min}$.

EFFECTS OF NONCONDENSABLE GASES AND LIQUID WATER ON OXIDATION PROCESS

The presence of noncondensable gas other than H_2S (for example, CO_2 , H_2 , CH_4 , NH_3 , and N_2) does not affect the H_2S removal capability of the oxidation process. Effects of these gases on H_2S removal were studied by introducing

TABLE 1. Summary Data for Catalyst Evaluation Test

RUN NO.	124	125	129	138	140	142	159	159-1 ⁽¹⁾	159-2 ⁽¹⁾	159-3 ⁽¹⁾	163	163-1 ⁽²⁾	167 ⁽³⁾
CATALYST	5	6	5	5	5	5	5	5	5	5	1	1	5
WT. OF CAT. gm	80	80	80	80	80	80	80	76.6	80	70.7	80.0	80.0	80.0
BED VOLUMEN, cm ³	128.8	184.0	131.7	131.0	130.3	132.5	117.8	117.8	126.6	141.3	170.7	135.4	142.8
STEAM RATE, gm/cm ² /min	20.2	20.5	21.0	20.1	19.23	19.22	21.3	21.6	20.13	20.00	22.66	23.61	19.56
SPACE VELOCITY, /min	184.6	130.9	186.6	181.4	174.5	171.5	213.9	216.5	188.0	164.3	156.7	206.1	161.8
RESIDENCE TIME, sec	0.33	0.46	0.32	0.33	0.34	0.35	0.28	0.28	0.32	0.37	0.38	0.29	0.37
AIR RATE, ml/min	50	50	50	50	50	50	40	50	50	50	50	50	50
OXYGEN STOICHIOMETRIC INLET	1.59	1.52	1.47	1.50	1.61	1.68	1.14	1.63	1.56	1.63	1.44	1.55	2.09
1 HR	197.9	205.2	207.8	216	207	200	220.5	188.4	207.3	201.3	193	208.2	182.0
2	0.5	0.6	0.7	0	0.8	1.8	0.35	1.00	1.73	0.35	0.58	1.10	1.00
3	1.0	1.1	1.0	0.8	1.0	1.9	0.45	1.15	2.00	0.39	0.68	1.33	1.40
4	1.3	1.5	1.2	-	1.1	1.9	0.56	1.21	2.05	0.40	0.77	1.42	1.58
5	1.8	1.8	1.5	0.8	1.1	1.9	1.10	1.25	2.13	0.42	0.89	1.48	1.70
6	2.2	2.0	1.8	0.8	1.2	1.9	1.76	1.30	2.17	0.45	1.00	1.50	1.84
7	2.5	2.3	2.0	0.8	1.5	1.9	-	1.35	2.23	0.47	1.15	1.50	2.04
8	3.1	5.2	2.2	2.2	1.8	2.0	-	1.37	2.30	0.48	1.30	2.05	2.28
9	3.8	8.2	2.4	1.0	2.9	2.0	-	1.40	2.35	0.51	1.50	2.90	3.00
10	4.0	12.7	2.5	1.5	2.1	2.0	-	1.45	2.45	0.54	1.75	5.90	5.40
11	4.8	16.5	2.8	2.8	2.2	2.0	-	1.70	2.90	0.55	1.97	7.85	10.40
12	5.2	-	3.0	4.8	2.3	2.0	-	3.80	5.10	0.70	2.24	9.80	15.20
13	5.8	-	7.2	8.0	3.2	2.0	-	6.50	7.50	2.30	2.55	11.80	20.10
BREAKTHROUGH TIME, hr	6.3	-	12.3	13.0	4.6	2.0	-	9.0	9.90	4.55	2.91	13.75	-
AVERAGE OUTLET, H ₂ S ppm	-	-	-	-	-	-	-	-	-	-	27.8	16.15	11.95
OUTLET OXYGEN CONC, ppm	3.26	3.99	2.68	3.02	1.74	1.9	9.01	6.31	4.13	0.77	5.91	5.94	6.42
% H ₂ S REMOVED	57.5	52.4	47.6	49.0	60.1	63.4	13.8	54.1	53.17	59.18	42.48	51.91	88.80
	98.4	98.1	98.7	98.6	99.2	99.05	95.94	96.65	98.00	99.63	97.42	97.15	96.48

NOTE: (1) CARBON REGENERATED WITH DICHLOROETHANE
 (2) CARBON REGENERATED WITH CARBON DISULFIDE
 (3) CARBON PARTICLE SIZE 4 x 10 MESH

duced to the reaction system. Results show no significant harmful effects exist. In presence of NH_3 , the formation of $(\text{NH}_4)_2\text{SO}_4$ occurs. This can be easily removed from the catalyst by washing with water while the catalyst is being regenerated.

The failure in removal of H_2S from saturated steam was attributed to the blinding of active sites of the catalyst by steam condensate. This theory was confirmed by a bed resistance (electrical) measurement technique. When saturated steam was fed to the reactor, the electrical resistance of the bed was low, and the H_2S concentration in the outlet stream was high. On the other hand, when superheated steam was fed to the reactor, the bed resistance increased, and the outlet H_2S concentration was decreased. We conclude that liquid water covering the active sites of the catalyst is the main reason why the catalytic oxidation process fails to remove H_2S from saturated geothermal steam.

MINIMUM OXYGEN REQUIRED FOR THE OXIDATION PROCESS

Theoretically, the amount of oxygen required for the H_2S removal process is stoichiometric; for one mole of H_2S reacted, one half mole of oxygen is required as shown in Reaction (1). However, in a real situation more oxygen than stoichiometrically required must be supplied to the system for nearly complete H_2S removal. The amount of the excess oxygen is of importance to the overall H_2S removal process because the excess oxygen may also corrode the power generating equipment. We found that the amount of oxygen required for an effective removal of H_2S depends upon the kind of activated carbon used. The minimum oxygen requirement is between 1.2 and 1.5 times the stoichiometric requirement. The oxygen concentration in the effluent of the H_2S removal unit is in the range of 40 to 50 ppm. Under this oxygen concentration, it is believed that no severe corrosion of power generating equipment will occur.

REGENERATION OF SPENT CATALYST

Various regeneration schemes for the spent catalyst have been studied in our laboratory. Among them the solvent extraction method is considered the most promising regeneration process. Solvents used for the extraction of sulfur include CS_2 , $(\text{NH}_4)_2\text{S}$, and dichloroethane. The solubility of sulfur in CS_2 is high; however, CS_2 is a toxic and flammable solvent. The residual solvent in the CS_2 extracted carbon also causes problems in the reuse of the regenerated carbon. Reactivation of this kind of carbon needs quite a large amount of clean steam. $(\text{NH}_4)_2\text{S}$ is also a good solvent for extracting sulfur from carbon; however, recovery of the solvent has encountered some technical difficulties. The solubility of sulfur in dichloroethane is low. However, the solubility is very sensitive to change in temperature, which is desirable for recovering sulfur from the extracted solution. Sulfur can be extracted from carbon by using this kind of solvent at high temperatures and recovered from the solution at low temperatures by a crystallization technique.

Activities of spent carbons extracted by both CS_2 and dichloroethane have been partially restored to the original levels, and they have been reused in

activity of a catalyst. Various experiments show that regeneration of catalyst with the solvent extraction is feasible.

4. CONCEPTUAL PROCESS DESIGN

A conceptual process diagram is shown in Figure 4. Basically the process utilizes several reactors in a series. A three-reactor system will be used here for explanatory purposes. In Figure 4-a reactors 1 and 2 are "on-line" while reactor 3 is being regenerated. Geothermal steam passes through reactors 1 and 2 to remove H_2S , and the treated steam exits for power generation. In Figure 4-b reactors 2 and 3 are "on-line" while reactor 1 is being regenerated. Figure 4-c shows that reactors 3 and 1 are "on-line", and reactor 2 is being regenerated. With this operating sequence the capacity of the catalyst can be fully utilized while maintaining a high H_2S removal efficiency. Solvent with different sulfur concentrations is stored in three (or more) tanks. The spent catalyst is first extracted with solvent having the highest sulfur content stored in Tank I. The effluent is pumped to an evaporator where elemental sulfur is recovered. The energy required for solvent evaporation is supplied either from the exhaust steam of a turbine power generator or from a low grade geothermal steam or brine. The spent catalyst is then extracted with solvents having lower sulfur concentration stored in Tank II. The effluent of the extraction is stored in Tank I. The final step is extraction by pure solvent stored in Tank III with the effluent of the extraction stored in Tank II. Solvent vapor from the evaporator is recovered in a condenser and goes to a surge tank and finally is pumped to Tank III.

When a solvent with a sulfur solubility sensitive to temperature variation is used, a high-temperature extraction and a low-temperature sulfur separation will be used. Dichloroethane is a solvent of this type. In the extraction a hot solvent is pumped to the reactor, and the spent carbon is soaked in the solvent for a period of time. The hot solution is then discharged to a crystallizer where the solution is cooled and sulfur crystals form. The sulfur is then separated from the solution in a centrifuge. The cold mother liquid is pumped through a heater and back to the reactor for another run of extraction. The same operation is repeated until most of the sulfur is removed from the spent carbon.

5. POTENTIAL ADVANTAGES AND PROBLEMS OF THE PROCESS

Major potential advantages of the catalytic oxidation process are:

1) Use of a Cheap Catalyst

The catalyst, activated carbon, used in the process, is readily available and relatively inexpensive. Activated carbon has been used in many different industries. The mass production of activated carbon is possible; various raw

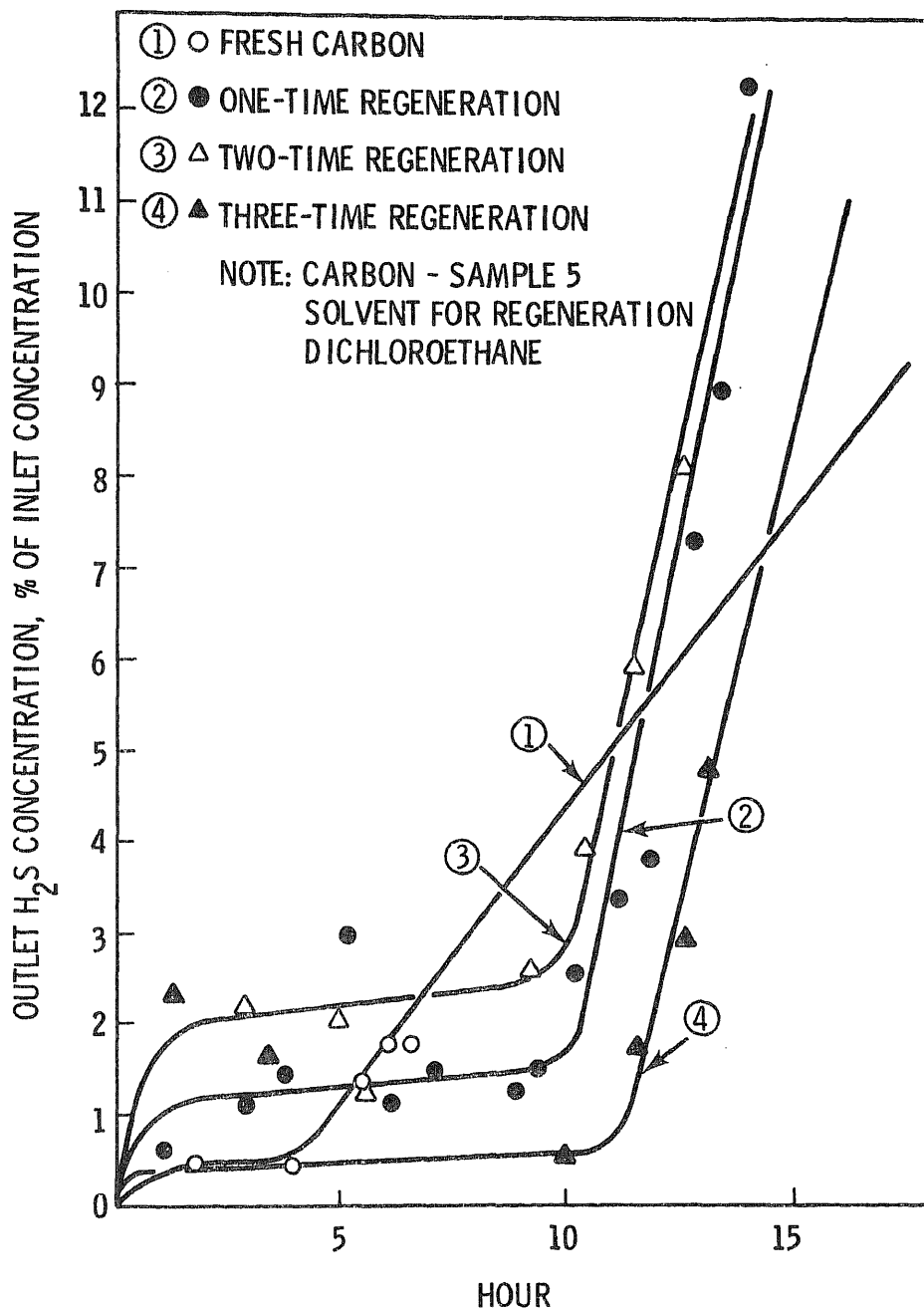


FIGURE 3. Outlet H_2S Concentration vs. Time for Regenerated Carbon

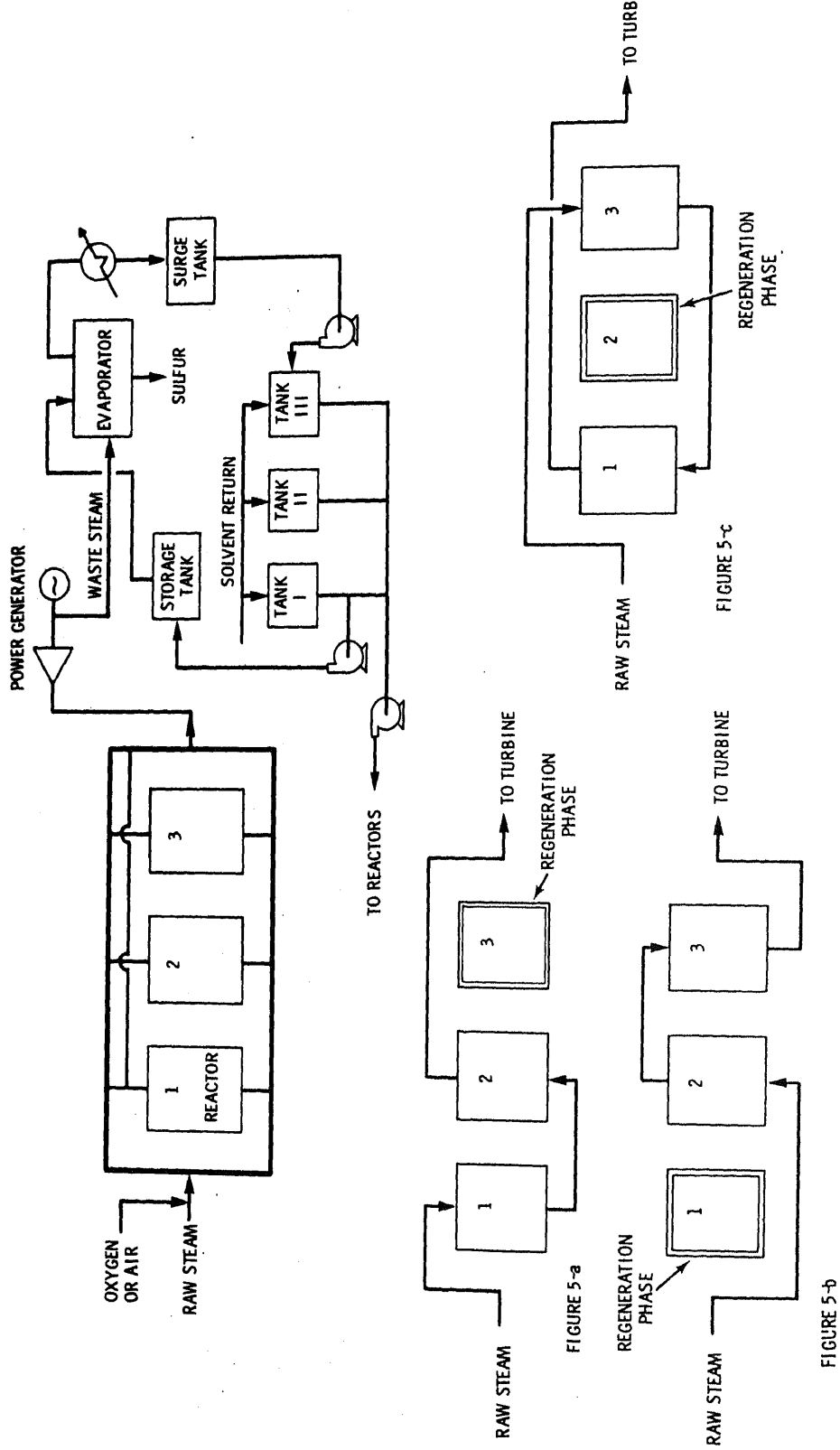


FIGURE 4. Conceptual Process Design

The use of pure oxygen is not necessary in the oxidation process. Oxygen required in the process can be supplied as either air or pure oxygen. In the H_2S removal process, oxygen is actually the only active ingredient which reacts with H_2S to form H_2O and S . Except for the cost of air compression, the oxygen needed for the H_2S removal process is essentially free.

3) Use of Regenerated Carbon

The activated carbon can be regenerated and reused. Although some minor technical problems in regeneration of the catalyst still need to be solved, results of experiments show that the consecutive use of regenerated carbon is possible. The use of the regenerated catalyst in the H_2S removal process will definitely reduce the operating cost of the process.

4) Recovery of Elemental Sulfur

Rather than removing H_2S from geothermal steam as other sulfur compounds, the oxidation process converts H_2S directly to elemental sulfur. The sulfur is later recovered by a solvent extraction process from the spent carbon.

5) No Problems in Disposing of Byproduct and Process Waste

Byproduct and process wastes do not create any disposal problems. The process byproduct--sulfur--is a very stable chemical element. It can be stored in an ambient condition or used as a raw material in other industries such as sulfuric acid production. After much reuse, the activity of the carbon decreases to a point where further regeneration of the carbon is either too difficult or economically too expensive. At this point, the exhaust carbon must be discarded. Because the exhaust carbon is merely a mixture of carbon and sulfur, disposal of this process waste will present no difficulties.

6) Simple to Operate

Overall, the oxidation process is simple to operate. The only chemical reaction (excluding side-reactions) in the entire process is Reaction (1) which takes place in the reactor. Solvent extraction and sulfur recovery involve only unit operations. Because of the simplicity of the process, it is expected to be easily adopted by either the steam supplier or the power producer of the geothermal power generating system.

Potential problems we foresee, before the catalytic oxidation process can be commercialized, are:

1) The Pressure Drop of Steam Across the Catalyst

The use of a packed bed reactor will always have a pressure drop, which is undesirable in a power generation system. The power loss in the steam treatment unit is proportional to the pressure drop of steam across the bed. Since the allowable sacrifice of the quality of steam in the treatment unit is limited, the amount of catalyst charged to the reactor to accomplish the required H_2S removal is very critical. High-activity carbon is required for both H_2S removal from geothermal steam and keeping the pressure drop to a minimum. The choice of a proper particle size of catalyst and reactor configuration will also help to reduce the undesirable pressure drop. Minimization of the pressure drop within the constraint of effective H_2S removal must be carefully studied.

2) Development of H_2S Removal Process for Saturated Geothermal Steam

The development of a H_2S removal process for saturated geothermal steam is urgently needed. The oxidation process we have been developing only applies to superheated geothermal steam. Unfortunately, most geothermal steam to be used for the power generation is obtained from the flashing of hot geothermal water (or brine); therefore, most geothermal steam is in a saturated condition. We are investigating two processes to overcome this problem: the throttling process and steam superheating process.

By adiabatically throttling a saturated steam, one can obtain a superheated steam of lower temperature and pressure. The change in steam condition from the saturated to the superheated by this method will solve the H_2S removal problem; however, it will also affect how much power can be generated. Superheating the steam with part of the electricity generated in a steam superheater can also solve the H_2S removal problem. The efficiency of turbine power generator and the efficiency of the steam superheater will govern the overall power production. Between these two modified processes for the removal of H_2S from the saturated steam, the most favorable process in terms of the maximum power production will be chosen for the future power plant application.

3) Improvement of Catalyst Regeneration Processes

Improvements of the catalyst regeneration process are required. Studies, to date, have used only CS_2 and dichloroethane for the extraction of sulfur in the catalyst regeneration process. Both are toxic solvents and must be handled carefully. Other nontoxic solvents which can effectively extract sulfur from the spent carbon should be sought so that a regeneration method with zero pollutant discharge may possibly be developed.

4) Effects of Trace Amounts of Heavy Metals in Geothermal Steam

Effects of trace amounts of boron and heavy metals such as mercury and arsenic, which are present in most geothermal steam, on the activity of the catalyst is unknown. In laboratory experiments, boron, mercury and arsenic were not included in the simulated geothermal steam. Effects of these elements must be studied. Any harmful effects on the activity of the catalyst due to the presence of these trace materials may make the oxidation process useless and require some modification of the process to remove these elements.

and the spent catalyst can be regenerated and reused. The next step is to design a pilot plant and evaluate the process by actual field tests. We believe that only through field tests the technical soundness and economical merits of the process can be realized. We are seeking sponsors to support this vital field test program.

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1. INTRODUCTION

The ferruginous hawk (Buteo regalis) is the largest member of the North American hawk family and is recognized as a species sensitive to disturbance and thus prone to nest desertion, especially during incubation (Olendorff and Stoddart, 1974; Fyfe and Olendorff, 1976; Woffiden and Murphy, 1977). Because of this sensitivity and its apparent declining numbers over parts of its range it has been placed in a category of special concern by allocating it to a "blue list" (American Birds, 1972). This list indicates species that are - or seem to be - substantially reduced in numbers, either regionally or throughout their range, due to any of a number of reasons, including habitat reduction and human impact. Further, during years where high population densities occur in its food base the hawk can be common and have high reproductive output (Olendorff, 1973; Woffinden and Murphy, 1977). These facts taken together make the ferruginous hawk a good barometer to the effects of human disturbance as might be found during geothermal development.

The ferruginous hawk has been studied over a number of years in the Raft River Valley area of southcentral Idaho (Power et al., 1973; Howard, 1975) and consequently its population densities and dynamics are known. Such previous baseline data are essential to establishing trends in populations and separating the effects of human factors from the environmental vagaries.

With the intensifying demands of multiple land use and the rapidly expanding efforts to diversify the uses of certain renewable and non-renewable resources, conflicts with wildlife and aesthetic values are increasing. The obvious meeting-ground for such conflict is in the wise use of each resource and the adjustment of activities to minimize

et al., 1977; Wagner, 1977).

The goals of this study were to use the ferruginous hawk as a barometer to the limits of impact, determine what sorts of "buffer zones" need to be established around the species to be compatible with the concepts of multiple use, and accumulate information and baseline data that will be useful to other studies aimed at determining similar parameters and rationales.

2. STUDY AREA

The study area surrounds the Raft River Geothermal Test Site in Raft River Valley, Idaho (Fig. 1). The most distant nests extended about 38 km north of the KGRA, and 19 km to the southwest. From north to south the study area covered about 49 linear km and from east to west about 33 km.

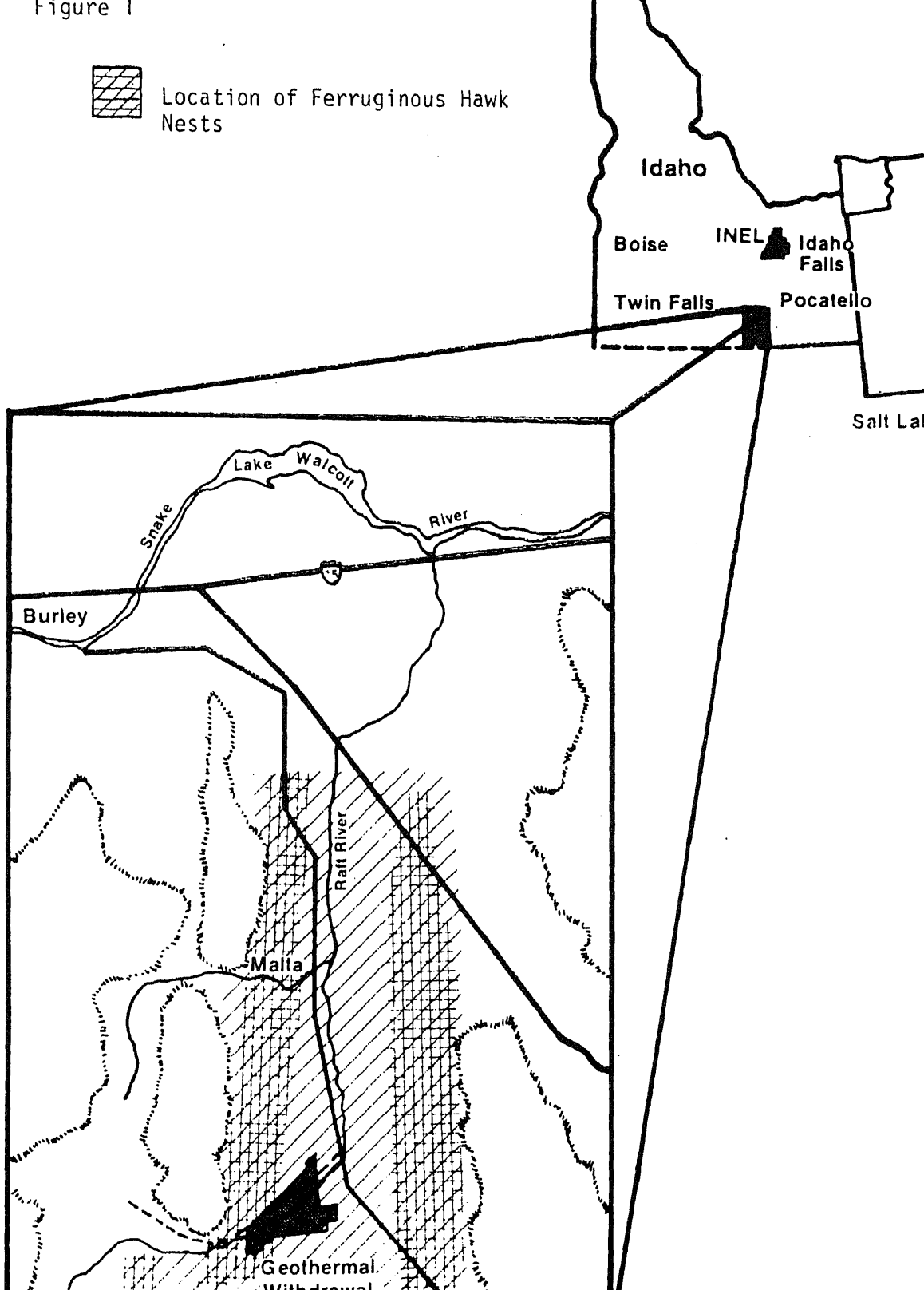
The habitat is typical of the Great Basin cold deserts. A mixture of sage (Artemesia sp), greasewood (Sarcobatus sp), rabbit brush (Chrysothamnus sp) and other low growing shrubs and forbs cover the valley floor. The gently sloping alluvial fans forming the sides of the valley and ascending to the higher mountains are covered with junipers (Juniperus sp). Generally, the outermost periphery of juniper that extend as tongues out into the sagebrush flats contained the nests.

3. MATERIALS AND METHODS

The study area was first visited on 6 - 7 April, 1978, to check for occupied territories. Territories had been located in previous years by Howard (1975). Nests were examined with a spotting scope from a distance of at least 1/4 mile but only long enough to determine if adults were present. Once occupancy was determined, treatment nests were chosen on the basis of accessibility or suitability for the given treatment. The area was then visited again on 3 May to start the impact treatments.

Five different impact treatments were originally planned but only 4 could be executed due to inappropriate conditions to accomplish the fifth. These treatments were undertaken as follows: a) 3 nests were visited on foot; b) 3 were visited by vehicle; c) 3 were disturbed by discharging firearms in the vicinity; and d) 2 were disturbed by placing continuously operating motors near them. Briggs and Stratton 3-1/2 hp gas engines were placed by nests and continuously supplied gas from a 211 l drum connected by a gravity-flow line. The engines were checked from a distance to determine only if they were operating. When they were known to have stopped due to rain or other factors they were then approached in vehicles and restarted. A firearm (0.22 cal rifle) was discharged approximately every 20 m as we approached the nest beginning with an approximate distance of 500 m from the nest and continuing until the adult flushed.

Figure 1



by two or three observers and was recorded to represent the or anxiety at which the hawk would no longer tolerate the presence of the disturbing factor. Once the hawk flushed we immediately retreated from the nest area.

All nests contained eggs at the initiation of the various treatments. An attempt was made to visit each nest daily through the presumed incubation period. Once nestlings were known to be in the nest, the frequency of visits was reduced. Nests were not climbed to determine clutch size. Once nests were known to be deserted or otherwise destroyed, remaining eggs were removed.

Data recorded included the general behavior of adults, their presence or absence, their time of arrival at nests if not immediately present, time of visit, and conspicuous environmental conditions such as rain, etc. Once eggs hatched, and nests were visited for banding, food remains were recorded and removed from the nests. Data were also taken on nearest nesting raptor of another species. All young were banded with U. S. Fish and Wildlife Service bands in control and treatment nests when about 2-3 weeks of age.

The density of the rabbit population was assessed by walking 10, 1.6 km transects chosen at random using the flushing distance equation of Hayne (1949) and the correction factor and census criteria of Gross, et al. (1974). This technique was used in order to compare with the long-term rabbit population data previously and concurrently taken by Utah State University for the general southern Idaho-northern Utah area adjacent or near to Raft River Valley (Gross, et al., 1974).

4. RESULTS

Unlike previously reported findings of nest desertion as a function of human interference, we witnessed very little nest failure caused by our treatments. Of the 11 treatment nests, only 3 pairs deserted eggs from what appeared to be our impact. These nests were deserted after 14, 10 and 8 days of impact and involved, respectively, two nests that were walked to and one driven to.

Each pair had slightly different responses to our treatment and none seemed to increase tolerance to our presence over time. Several pair did not show any apparent increased sensitivity to the treatment. The results of the treatments are shown in Table 1.

Two of the treatment nests failed due to natural causes and not our interference. One was partially blown from the nesting tree; the eggs could not be incubated and thus were deserted. The second nest was blown from the tree after the young were approximately 14 days old; the young were subsequently lost to predation after 4 days. Two of the young were found dead about 30 m from the nest 2 weeks after their disappearance, and appeared to have been removed from the nest by an avian predator, possibly a raven. The possible mammalian predators in the area would most likely have eaten the young had they removed them from the nest.

TABLE 1

IMPACT TREATMENT AND RESULTS AT EACH NEST

Nest Number	Treatment	Date Treatment Started	Date Treatment Ended	Number Of Visits	Mean Flushing Distance and Range (m)	Results	Comments
1	Walk	May 3	June 2	18	31 (14-137)	Depredated	Hatched destroyed ca. May
9	Motor	May 13	June 12	8	65 (37-201)	Fledged 4 Young	--
11	Gun shots	May 11	June 21	18	71 (23-320)	Fledged 2 Young	Eggs hatched May 18
15	Drive	May 10	May 18	7	217 (18-484)	Deserted	--
17	Gun shots	May 10	June 22	22	96 (5-274)	Fledged 2 Young	Eggs may be by May 1
19	Drive	May 10	May 17	6	221 (137-366)	Destroyed	Nest des wind
22	Drive	May 10	June 22	25	62 (18-484)	Fledged 1 Young	Eggs hatched May 19
24	Walk	May 4	May 17	8	110 (23-183)	Deserted	--
31	Gun shots	May 10	June 22	19	74 (5-320)	Fledged 4 Young	Eggs may be by May 1
33	Motor	May 5	May 29	8	101 (37-320)	Fledged 4 Young	Eggs may be by May 1
36	Walk	May 4	May 4	6	53 (37-91)	Deserted	--

perhaps should have been eliminated from the sample). These 10 nests fledged a total of 55 young, for a fledgling success of 3.44 young per nest. The controls and successful treatment nests were not significantly different where $P=0.1$ confidence level, as tested by a paired comparison t-test. However, a pattern appeared in that the control nests fledge better than one-half young more per nest. This difference may be nonetheless of biological significance. Considering all treatment nests the difference between the controls and treatment nests is significantly different where $P=0.05$ confidence level. This difference results from the desertion of nests which we view as a result of our insult upon them.

In addition to the nests examined in Raft River Valley we also checked 15 nesting locations in the adjacent Black Pine and Curlew valleys. Only 5 successful pairs and 2 additional nests that had contained eggs but were recently destroyed by wind were found. The 5 nests produced 15 young for a fledgling rate of 3.0 young per pair. Reproduction in these pairs more closely approximates our treatment than control nests. We suggest that the difference in fledgling rate between these two valleys and the controls in Raft River Valley is a result of the lowered food base in the former areas. Data to support this are presented beyond. Woffinden and Murphy (1977) have already shown a correlation between jackrabbit density and nesting success and fledgling rate in the ferruginous hawk.

During the course of this study 78 raptor nests representing nine species were found. Most were found incidental to the study but the three species (ferruginous hawks, Swainson's hawks, and long-eared owls) commonly using the juniper forest and nesting close to the ferruginous hawk had rather complete data gathered on them. The one species that was unfortunately neglected but that interacts closely with the ferruginous hawk is the raven. In decreasing numbers of nests found the nine species are: ferruginous hawk, Swainson's hawk, long-eared owl, red-tailed hawk, golden eagle, great-horned owl, burrowing owl, cooper's hawk and prairie falcon. Additionally, the American kestrel, harrier, short-eared owl, and sharp-shinned hawk nested in the valley, but data were not gathered on them because of lack of time or opportunity.

Two interesting nesting associations exist between the ferruginous hawk and other functional raptors. The raven used old ferruginous hawk nests and in point of fact both species may exchange nests and territories in subsequent years. They appear to defend mutually exclusive territories. Of 15 active ferruginous hawk nests sampled, 14 or 93% had an active Swainson's hawk nest within an average of 0.60 km from it. Of 15 territories used in past years but not occupied by ferruginous hawks in 1978, only three or 20% had active Swainson's nests near them, these within an average of 0.36 km. Most of the other 11 territories, however, had unused Swainson's hawk nests around them and in most cases also within 0.60 km.

ferruginous hawk nests sites within a sample radius of 0.80 km. This association was further confirmed when we located two additional Swainson's hawk nests in an area where ferruginous hawk were not known to be. A search around the Swainson's nests revealed an active ferruginous hawk nest within 0.80 km of one and about 1.12 km from the other. The ferruginous hawk in the latter case nested out in an isolated tree (may have been a second attempt nesting) with no other trees closer than 1.12 km. The Swainson's hawk thus used the nearest set of available trees. Reasons for the association as mentioned above are unclear and will be explored and further documented in 1979.

The distribution of the ferruginous hawk with respect to the available habitat is rather uniform. The juniper habitat occupied by the hawk is more or less continuous in a belt along both sides of the valley. Because the hawks, however, occupy the outer periphery of juniper stands, outlying single trees, or small clumps of several trees, one gains the impression of a patchy or clumped habitat and related nesting distribution. Of 8 active nests along the east side of the valley the average distance between them was 3.9 km (range 1.6 to 6.4 km) over 24 linear km. On the west side of the valley, including an extension ridge at the south end of the valley, 17 active nests were separated, on average by 4.7 km (range 0.8 to 8.0 km) over 46 linear km. The closest nests to one another across the valley of unsuitable habitat comprising either brush or farmland was 8 km. This distance was between a tree nest and the only ground nest we located. More characteristically, however, the distance across the valley between nests is about 12.8 km.

Food habits were partly assessed by examination of prey remains in nests. Once it became evident that both species relied heavily on rabbits (89.4% for ferruginous and 81.1% for Swainson's hawk on a biomass basis) rabbits were counted along transects (Hayne, 1949; Gross, et al., 1974). Within Raft River Valley proper (area of about 309 km²) the rabbit density was high with about 1286 rabbits per km². This is high by most standards but includes the year's crop of new juveniles which most counts do not include (cf. Gross et al., 1974) since they are taken when only the adult breeding population is counted in early spring or late autumn. Highs in the adult breeding population at these times are indicated by counts on the order of 100 to 200 individuals per km².

5. DISCUSSION

As with most biological subjects there does not appear to be a single standard formula or level of development related impact that can be applied to the ferruginous hawk. Although a variety of impacts from geothermal development have been suggested (Ermak and Phelps, 1978) little is known about the distance the impact is effective. Under the conditions of our study we suggest that normal human activities at distances greater than

zone" we suggest is then 1.0 km.

It appears that our data would have been different if we had started our treatments at or just prior to the onset of egg laying, or had the food base been at low density. We suggest that the threshold of sensitivity is lowered significantly when the adults are in a poor physiological state as they would be in food stress situations. Such lowered physiological condition in poor food years is evidenced by smaller clutch sizes and fewer nesting pairs (cf. Woffinden and Murphy, 1977). In 1979 we will start our treatment at the onset of egg laying or incubation to test one of these assumptions.

We are further convinced that the nest desertion process after one visit to the nests can be correlated with food availability. Such correlation seems not to have been attempted in most earlier studies. We made single visits to several different nests not included as a part of this study and climbed to them during incubation; the adults did not desert. We suggest, however, that had we climbed repeatedly to the nests in our study during incubation more desertions would have occurred. Grier (1969) could not demonstrate any effect on productivity at climbed and unclimbed bald eagle nests but he did not carry out his experiment during the incubation phase of the breeding cycle. Simple approach on-foot toward wintering bald eagles shows a significant adverse effect, however, on their flight distance and rooting behavior (Stalmaster and Newman, 1978).

Although we used flushing distance as indications of a critical stress threshold and interpreted the desertion of nests as manifestation of it we are aware that the hawks might well have reached a critical stress level long before they flushed. Busch, deGraw and Clappitt (ms) recorded a 3-fold increase in heart rate, as an indication of stress, at the sight of a human approaching a caged ferruginous hawk. Under our field conditions heart rates might well have increased at much greater distances than that distance at which the hawk flushed. We suggest that adults in our study became sensitized to us or our presence in the area and were not as attentive to their young as they otherwise would have been. This lowered attentiveness may indeed account for the lowered fledging success noted in this study. This is evidenced by at least two observations: 1) young hawks at one treatment nest were not brooded as they normally would have been during a severe rainstorm, and 2) during banding when the controls and treatment pairs had young 2-3 weeks of age, the treatment pairs were consistently absent from the nest or remained at great distances while the control pairs were close by the nests, appeared more concerned, and occasionally made weak defense gestures at us.

Although incubation may be successful and young raised, the presence of humans too near nests may cause the added problem of premature fledging of young which may increase their mortality. At one nest our presence caused a young, only recently out of the nest, to make an exerted and lengthy premature flight. Within 20 minutes a coyote (Canis latrans) was scouting the area where the young had landed. This coyote may have seen the young in its unstable flight or its presence might have been a chance event. Greater

being important to the outcome of several findings in this study. Food distribution or preference often plays a prime role in causing closely related animals to partition the available habitat to avoid interaction or even competition. This same food preference or distribution may, on the other hand, act to draw species together. Because the habitat has such uniformity we doubt it would act in causing Swainson's hawks to be closely associated in nesting with ferruginous hawks. At first glance then, we thought food might be the factor causing this association and that Swainson's hawks were cueing in on active ferruginous hawk nests as an indication of an available food supply since both species take a similar amount of rabbit in the diet. In the ferruginous hawk this amount was 89% and in Swainson's hawk 81% on a biomass basis. However, the values are biased in the case of the Swainson's hawk since it will often take carrion road-killed rabbits to the nest. Further, on a biomass basis jackrabbits make up 89% of the total rabbits in ferruginous hawk while only 58% in the Swainson's diet, the remainder being cottontail and pygmy rabbit.

As a measure of the amount of overlap in foods the Kulczynski index in similarity is frequently employed as described by Oosting (1956) (cf. also Ueckert and Hansen, 1971). Using this method an index of 90 shows high or nearly total overlay while an index of 10 is a low degree of overlap. On a biomass basis the 4 most common mammals in the ferruginous hawk diet (94.2% of total) only had an index of similarity of 64.5 with the Swainson's hawk. On a numerical basis of individuals taken in the diets the index of similarity was 55.8 for mammals, 7.9 for birds and 52.4 for the entire diet.

These indices suggest that the degree of overlap is not great and probably the parameters of food are not related to the reasons for the association of the two species. They appear to be associated in nesting proximity, although less closely, even where food overlap approaches 90-95% as it does in Alberta (Schmutz, 1977).

Continued observation and experimentation are required to adequately understand and predict the long-range impacts that geothermal development may have on the population dynamics of ferruginous hawks in the Raft River valley. The concept of utilizing biological subjects as "indicator organisms" is not new, and use of such information by industry in selecting locations for future development could mitigate potential problems and/or delays associated with destruction of critical habitat. In this study we have attempted to observe the natural behavior of the raptors under both disturbed and undisturbed conditions to determine the level of perturbation that the organisms will tolerate without decreasing nesting success or production rates. Utilizing such information as siting criteria for well and/or power plant locations should enable development to take place compatibly with species normally sensitive to such development.

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SESSION 5

ENVIRONMENTAL CONTROL ASPECTS OF SOLAR ENERGY USAGE

Chairman: John Mock

Co-Chairman: M. R. Riches

AN OVERVIEW OF PHOTOVOLTAIC ENVIRONMENTAL ISSUES

Kathryn A. Lawrence
Solar Energy Research Institute

Photovoltaic cells have been termed one of the most benign electricity sources yet conceived. This is certainly true of the plant operation phase, i.e., the period during which electricity is generated and supplied to the consumer. However, no form of energy production is without potential environmental impact, including electricity generation via photovoltaic cells. This paper summarizes the environmental issues associated with each phase of the life cycle--resource extraction and processing, cell manufacture, system installation and operation, and system decommission. The primary focus is on the semiconductor materials themselves and on centralized energy facilities rather than distributed systems; energy storage systems are not addressed. Photovoltaic systems are materials intensive compared to fossil fuel electric plants with the same power rating. As a result, extraction and processing of resource inputs for cell production (silicon for silicon cells; cadmium, sulfur and copper for cadmium sulfide cells [CdS]; gallium and arsenic for gallium arsenide cells [GaAs]) will release significant quantities of particulates as well as other toxic air emissions, miscellaneous water pollutants, and solid wastes. The greatest potential for adverse environmental effects occurs during cell manufacture. Production of all three cell types will emit significant quantities of particulates. Cadmium sulfide cell production could release as much as 34 T cadmium, 52 T cadmium sulfide, and unspecified quantities of cadmium oxide fumes per 10MW_e cells. System operation is relatively benign. None of the cell types emit air or water pollutants under normal operating conditions. However, toxic fumes could be released, particularly from CdS or GaAs systems, in the case of fire. Facility decommission should present no serious environmental hazards for silicon cell systems. However, disposal or recycle of spent CdS and GaAs cells will require care and further research attention.

ENVIRONMENTAL CONTROL TECHNOLOGY IN THE SOLAR
PHOTOVOLTAIC INDUSTRY: NOW AND IN THE FUTURE

N. R. Hild and M. G. Coleman
Motorola, Inc.

Manufacturing of solar cells is performed with process steps commonly utilized in the semiconductor industry. Present process sequences incorporate a broad spectrum of wet chemistry steps for etching and cleaning and utilize large quantities of hazardous gases in high temper-

cost factor in today's manufacturing. Ultimately limited by the cost of consumed materials, both for utilization and for disposal, an economic driving force exists to reduce materials consumption. Manufacturing sequences of the future will be simpler and consume fewer materials than sequences now utilized. Savings will be realized through replacement of some wet chemistry steps with dry processes. Ion implantation will replace gaseous diffusion. Emphasis will be to minimize consumed materials and to recycle by-products. Example manufacturing sequences will be presented.

AN OVERVIEW OF SOLAR THERMAL ELECTRIC SYSTEMS ENVIRONMENTAL ISSUES

R. G. Lindberg
University of California, Los Angeles

Attractive features of solar energy for production of electricity include an inexhaustible and virtually free energy source as well as very minimal impacts on air quality relative to conventional power plants.

The two major applications of STPS technologies are (1) large scale (300-500 MWe), centralized receiver systems, and (2) smaller scale (0.5-10 MWe), dispersed receiver systems applicable for either or both electric power generation and heat production. Environmental concerns vary significantly with the application.

Large scale centralized STPS are land, water, and capital intensive. Major environmental concerns derive from siting such facilities in southwestern deserts. The principal environmental concerns are for potentially irreversible ecological impacts in the vicinity of STPS sites, and worker safety on-site. The primary siting constraint will be availability of water.

Smaller scale, dispersed receiver, STPS are likely to be located near areas already developed for agriculture or industry. The primary environmental concern will be public safety and protection of property. The primary siting constraint will be institutional barriers associated with land use, zoning, utility interfaces, etc.

Representative areas requiring further assessment are handling and disposal of system fluids and wastes; consequences and mitigation of accidental releases of working fluids; consequences and mitigation of normal and misdirected heliostat reflection; possible alterations of local ecosystems and microclimates near heliostat fields; and socioeconomic and institutional constraints to adoption of STPS technology.

T. D. Brumleve
Sandia Laboratories, Livermore

Potential eye hazards associated with reflected light from the heliostat arrays of central receiver power plants have been investigated analytically and experimentally. Techniques were developed for measuring image sizes and irradiance levels relative to safe exposure limits for the human retina at various distances for single and multiple heliostate beams. Results of experimental measurements in single beams are given for four different types of heliostats at Sandia Livermore. Multiple beam measurements were made by means of helicopter flights over the Solar Thermal Test Facility heliostat array at Sandia Albuquerque. Potential exposure levels for aircraft personnel above minimum altitudes specified by general FAA rules were found to be well within safe limits.

SAFETY AND ENVIRONMENTAL IMPLICATIONS.
DOE/SANDIA MIDTEMPERATURE SOLAR SYSTEMS TEST FACILITY

James A. Leonard
Sandia Laboratories

The Department of Energy/Sandia Laboratories Midtemperature Solar Systems Test Facility in Albuquerque, New Mexico, has been in operation since late 1975. The MSSTF was constructed in support of the DOE's national small Solar Power Systems Program. Its objective is to develop technology for applying solar energy on-site to electrical power generation and other higher temperature applications such as industrial process heat. The MSSTF is, at 32 kWe, the largest solar electric power plant in the U.S. and also represents the world's first application of the solar total energy concept to an actual load, an 1100 m² office building. Many of the operations at the MSSTF have safety and environmental implications. Several examples are: concentrating solar collectors which focus sunlight to a concentration ratio of up to 200 and can raise the temperature and pressure of heat transfer fluids to 330°C and 18 MPa; 315°C sensible heat storage systems with capacities up to 24000 liters of Therminol-66; an organic Rankine cycle turbine/generator operating on superheated toluene. This presentation described the MSSTF, reviews the facility design considerations relative to safety and environment, summarizes relevant operational experience, and projects these design considerations and operational experience to larger solar thermal application projects and to

During the 1970s the use of solar energy for heating and cooling of buildings and for process heat for agricultural and industrial purposes has been developing rapidly through private and governmental efforts. Although these solar technologies appear to be environmentally benign, they offer the potential for some significant health and safety problems. The DOE program in solar environmental assessment is intended to anticipate problems and devise solutions to them.

A major part of this effort is the drafting of an environmental impact statement for the solar heating and cooling program and an environmental assessment for the program in agricultural and industrial process heat. These draft reports should be released for public comment during the coming year.

A major current concern is the use of liquid heat transfer fluids in active solar systems. Many of these fluids and probably some of the additives in them are combustible and toxic. The combustibility problem is being dealt with by development of a residential standard on flash points of the liquid heat transfer fluids. The toxicity problem is being dealt with by bacterial screening tests and animal testing. None of the liquid heat transfer fluids tested to date show significant mutagenic activity in bacterial screening tests or unusual toxicity to animals in oral and skin tests, not even when the fluids are subjected to extended periods of high temperature that could cause chemical changes.

Several other important studies are underway. One deals with the assessment of potential hazards associated with the final disposal of waste fluids. It is not yet certain how significant the influences could be on sewage treatment facilities and on soil (in the case of land disposal) when large numbers of solar systems are in use.

Jimmie Q. Searcy

Sandia Laboratories

The utilization of solar energy to heat and cool homes is a goal being promoted by federal, state, and local governments. As that goal is achieved, more and more homeowners and small businessmen will come face to face with unfamiliar technologies and materials. The potential SHAC materials present certain safety risks that have been identified. An ongoing effort to develop a handbook of hazardous material properties and environmental effects caused by materials will also be described.

Safety risks - The chief safety risks associated with SHAC materials result because of the toxicity and fire properties of the materials. Toxicity and fire hazards will be reviewed for some of the more common SHAC materials.

Environmental Effects - Most potential environmental effects that can be mitigated by the designer and user of SHAC technologies result from disposal of materials. Methods of disposal of SHAC materials will be briefly reviewed, and potential negative environmental effects will be considered. Emphasis will be placed on liquid heat transfer fluids.

TOPIC: ENVIRONMENTAL CONTROL ASPECTS OF SOLAR ENERGY USAGE

From the perspective of the year 2000, mankind will look back on the 1970's as the dawn of the Solar Age. In 1973, the U.S. Government spent approximately \$4 million dollars on solar energy. Within five years that amount has multiplied by 100-fold. In FY '79, the U.S. Government will spend almost \$500 million to develop effective, economical, environmentally acceptable solar energy systems.

Within DOE, the solar program is divided into two parts. Under the Assistant Secretary for Conservation and Solar Applications, approximately \$110 million is budgeted for:

	<u>Million</u>
Demonstrations	\$ 56
Heating and Cooling	40
Agricultural and Industrial Process Heat . .	11.0
(Technology Support/Utilization)	2.8
	<u>\$109.8</u>

Under the Assistant Secretary for Energy Technology, approximately \$370 million will be spent on:

	<u>Million</u>
Photovoltaics	\$118.5
Solar Thermal	101
Wind	61
Ocean Thermal	39
Biomass	43
(Technology Support/Utilization)	6.7
	<u>\$369.2</u>

Let me spend a few minutes highlighting these technologies.

Solar heating and cooling systems, and solar systems to provide agriculture and industrial process heat are beginning to enter the marketplace. The primary efforts with these technologies will be to drive down the costs of the systems so they become competitive with other forms of energy.

high as 500 Mw in 1986; and to use this as a wedge into the utility market in the late 1990's--10 to 20 Gw by 2000.

Solar Thermal is the simplest and most direct use of solar energy, after the passive and space heating technologies. It is versatile, and can provide electricity, heat, and shaft work, individually or in combination. The 10 MWe central receiver facility at Barstow will be on line by 1981. The market for small power systems (less than 10 MW) is estimated to be 14.5 quads per year; the market for large power systems is 7 quads per year.

Small Wind Systems are used extensively throughout the world. They are versatile and can be sized from hundreds of watts to megawatts. It is expected that commercial small wind systems will be competitive in the early 1980's, and wind systems will be operating routinely in the intermediate utility market by the mid-1980's. General utility competitiveness is expected to be achieved in the late 1980's with a target of 2 quads in 2000.

OTEC Systems, i.e., Ocean Thermal Electric Conversion Systems, provide the only base load solar option. The ocean resource is enormous and provides its own storage. If successful, OTEC systems could contribute 0.5 quads by the year 2000. These systems will help promote island energy "independence" by the late 1980's. If successful, this experience will help us crack the utility market by the late 1990's.

Biomass is the largest solar contributor today -- 1.3 quads primarily in the forest products industry -- an additional quad by 1985. Biomass is capable of supplying fuels to the transportation sector and is a renewable hydrocarbon source of fuels, petrochemical substitutes, and other energy intensive products. It is the only solar technology which can be easily stored -- as biomass or fuels. This resource base could be very large, tens of quads, if marine biomass proves feasible.

In summary, we face a bright tomorrow. The problems facing us are primarily economical ones -- how do we reduce the costs of these new systems? At the same time, we must not neglect the environmental and socio-political problems that arise when any new technology is introduced no matter how benign the technology. For the remainder of the day, we will highlight and discuss with you the nature of these problems as we now see them. I encourage your active participation in this session.

Thank you.

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1. INTRODUCTION

Photovoltaic cells have been termed "the most benign source of electricity yet conceived" [1]. This is certainly true of the plant operation phase (i.e., the period during which electricity is generated and delivered to the consumer). However, no form of energy conversion is without potential environmental impacts, including electricity supplied by photovoltaic cells. This paper presents a brief overview of potential environmental impacts identified through critical path analysis of each of the life-cycle phases--resource extraction and cell production, plant construction and operation, and plant decommission. The potential risks associated with energy storage subsystems are not addressed.

2. ENVIRONMENTAL IMPACTS OF RESOURCE EXTRACTION AND CELL PRODUCTION

Photovoltaic cells are composed of semiconductor materials capable of converting sunlight into direct current electricity. A variety of crystalline and amorphous semiconductor compounds are suitable for use in photovoltaic cells. The major candidates at present are silicon (Si), cadmium sulfide (CdS), and gallium arsenide (GaAs).

Silicon cells are composed of a thin silicon crystal wafer[†] in which the semiconductor properties have been modified by doping (controlled additional of chemical impurities). A positive-negative (p-n) heterojunction is formed by addition of a p-type dopant (usually boron) and an n-type dopant (usually phosphorous). Quantities of silicon and dopants required per MW_e cells, along with information on resource availability, are summarized in Table 1. The environmental effects normally associated with resource extraction will occur and include site disturbance, fugitive dust and noise, temporary air and water degradation, etc.

A simplified production schematic for silicon photovoltaic cells is shown in Figure 1. In brief, quartz is purified to polycrystalline silicon, doped with a p-dopant, allowed to form crystals, doped with an n-dopant, sliced, and finished into a coated cell. Principal emissions associated with cell

*The views, opinions, facts and interpretations expressed in this paper are solely those of the author and do not reflect any policy, position, or view of the Solar Energy Research Institute.

[†]Research is also being conducted on amorphous silicon photovoltaic

TABLE 1. Resource Requirements

Resource Input	Metric Tons (MT)/ 1 MW _p Cells	Estimated Primary Domestic Production Capacity, 1985, MT ¹	Estimated Primary Domestic Demand 1985, MT ¹
<u>Silicon Cells</u>			
Silicon	4.6	671 x 10 ³	685 x 10 ³
<u>CdS Cells</u>			
Cadmium	0.4 - 0.8	2,721	7,800
Sulfur ²	0.2	14,512 x 10 ³	13,152 x 10 ³
Copper ³	3.0	2,268 x 10 ³	2,449 x 10 ³
<u>GaAs Cells</u>			
Gallium	0.27	10.0	9.5
Arsenic	0.14	2,900	22,770

¹Data taken from reference 8; estimates are for non-cell uses.

²Amount includes sulfur in the CdS and Cu₂S portions of the cell.

³Estimates are for copper in the Cu₂S barrier and the Cu-foil substrate.

*Source: Table developed based on information in references 2, 3, 6 and 10.

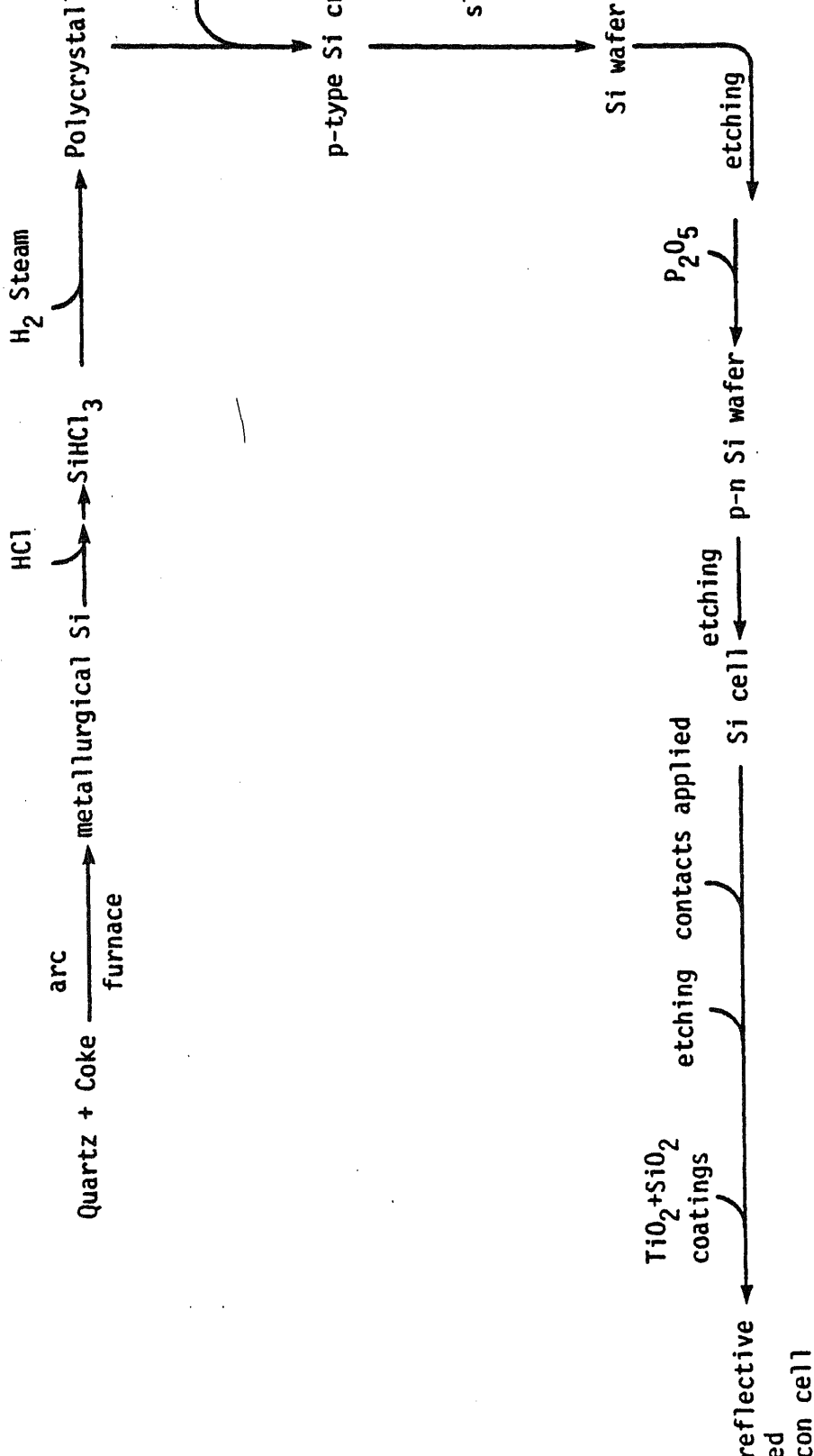


Figure 1 Silicon Cells: Simplified Production Schematic

production include sulfur oxides, nitrogen oxides, particulates (90% to 97% attributable to coal combustion to provide the required energy), and quantities of solid silicon compounds.

Production of cadmium sulfide (CdS) cells requires inputs not only of cadmium and sulfur, but also copper (to form a copper sulfide $[\text{Cu}_2\text{S}]$ layer). The CdS portion of the cell functions as a semiconductor and the Cu_2S portion as a barrier. Thus, the principal inputs are cadmium, sulfur, and copper.

Cadmium is acquired almost exclusively as a byproduct of zinc refining. The cadmium fumes are precipitated to form cadmium sulfate (CdSO_4). Cadmium sulfate is reacted with zinc dust and water to yield cadmium-sponge briquets, the primary starting materials for cell production. The sponge is heated, condensed, and reacted with sulfur vapors in the presence of argon gas to form CdS.

The CdS cells are formed by either successive vacuum depositions of CdS and Cu_2S on copper foil or by successive sprays of CdS and Cu_2S on float glass [2]. The CdS layer varies in thickness from 5μ to 30μ [3]. Simplified production processes are shown in Figure 2, and quantities of materials required per peak megawatt cells are listed in Table 1.

Emissions from CdS cell production include sulfur oxides, particulates, carbon monoxide, hydrocarbons, and nitrogen oxides, all attributable to fossil fuel combustion to supply energy to the cell production process [2]. Emissions unique to CdS cell fabrication include miscellaneous cadmium compounds, cadmium dust, cadmium fumes, and cadmium oxide (CdO); all are toxic and have TLV-TWAs[†] of 0.05 mg/m^3 [4]. In addition, quantities of hydrogen sulfide (H_2S) released during cell manufacture may adversely affect air quality and human health [5]. Levels of emissions have been estimated by one source [6] to be 31 MT(34 T) cadmium and 47 MT(52 T) cadmium sulfide per production of 10 MW_e cells. Because production is primarily a laboratory process at present, emissions from a commercial cell production facility may deviate significantly from estimates.

Cadmium is accumulated from air and water by plants. Although there is no evidence of bioconcentration in aquatic food chains, moderate cadmium pollution does adversely affect fish reproduction. In humans, acute oral doses can cause nausea, vomiting, and sometimes severe gastroenteritis. The effects of chronic ingestion are unknown. Inhalation of large amounts of CdO dust will produce pulmonary edema and, in some cases, death. Chronic inhalation (about 20 years) produces chronic emphysema and renal disturbance [7]. Thus, control of cadmium release is critical. Research is currently underway to determine the nature and magnitude of health risks associated with CdS cell production [5]. It should be noted that levels of emissions attributable to CdS cell production are low compared to total annual cadmium

[†] TLV-TWA = the time-weighted average concentration for a normal 8-hour workday or 40-hour workweek, to which nearly all employees

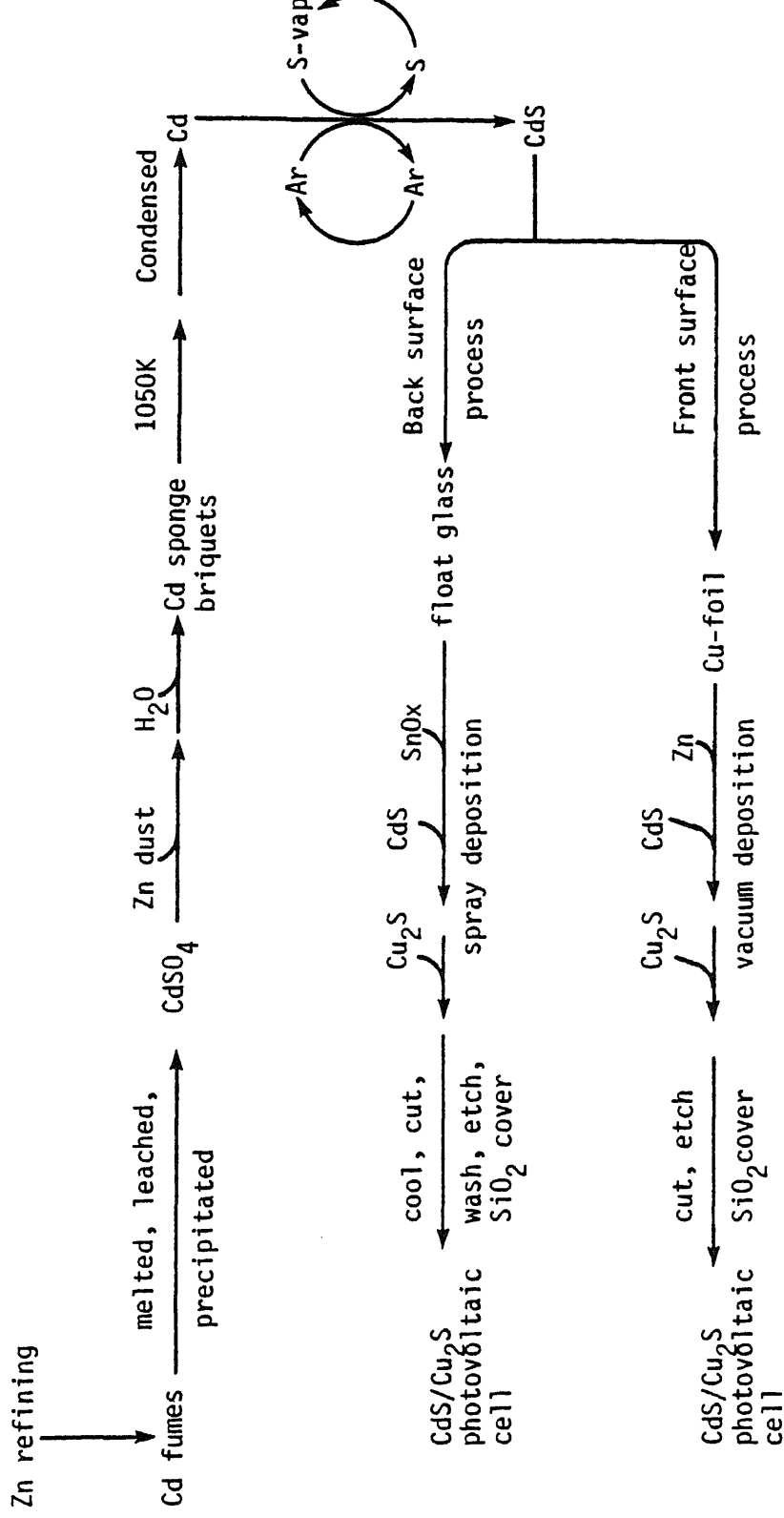


Figure 2 Cadmium Sulfide Cells: Simplified Production Schematic

emissions (e.g., emissions from 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65, 66, 67, 68, 69, 70, 71, 72, 73, 74, 75, 76, 77, 78, 79, 80, 81, 82, 83, 84, 85, 86, 87, 88, 89, 90, 91, 92, 93, 94, 95, 96, 97, 98, 99, 100, 101, 102, 103, 104, 105, 106, 107, 108, 109, 110, 111, 112, 113, 114, 115, 116, 117, 118, 119, 120, 121, 122, 123, 124, 125, 126, 127, 128, 129, 130, 131, 132, 133, 134, 135, 136, 137, 138, 139, 140, 141, 142, 143, 144, 145, 146, 147, 148, 149, 150, 151, 152, 153, 154, 155, 156, 157, 158, 159, 160, 161, 162, 163, 164, 165, 166, 167, 168, 169, 170, 171, 172, 173, 174, 175, 176, 177, 178, 179, 180, 181, 182, 183, 184, 185, 186, 187, 188, 189, 190, 191, 192, 193, 194, 195, 196, 197, 198, 199, 200, 201, 202, 203, 204, 205, 206, 207, 208, 209, 210, 211, 212, 213, 214, 215, 216, 217, 218, 219, 220, 221, 222, 223, 224, 225, 226, 227, 228, 229, 230, 231, 232, 233, 234, 235, 236, 237, 238, 239, 240, 241, 242, 243, 244, 245, 246, 247, 248, 249, 250, 251, 252, 253, 254, 255, 256, 257, 258, 259, 260, 261, 262, 263, 264, 265, 266, 267, 268, 269, 270, 271, 272, 273, 274, 275, 276, 277, 278, 279, 280, 281, 282, 283, 284, 285, 286, 287, 288, 289, 290, 291, 292, 293, 294, 295, 296, 297, 298, 299, 300, 301, 302, 303, 304, 305, 306, 307, 308, 309, 310, 311, 312, 313, 314, 315, 316, 317, 318, 319, 320, 321, 322, 323, 324, 325, 326, 327, 328, 329, 330, 331, 332, 333, 334, 335, 336, 337, 338, 339, 340, 341, 342, 343, 344, 345, 346, 347, 348, 349, 350, 351, 352, 353, 354, 355, 356, 357, 358, 359, 360, 361, 362, 363, 364, 365, 366, 367, 368, 369, 370, 371, 372, 373, 374, 375, 376, 377, 378, 379, 380, 381, 382, 383, 384, 385, 386, 387, 388, 389, 390, 391, 392, 393, 394, 395, 396, 397, 398, 399, 400, 401, 402, 403, 404, 405, 406, 407, 408, 409, 410, 411, 412, 413, 414, 415, 416, 417, 418, 419, 420, 421, 422, 423, 424, 425, 426, 427, 428, 429, 430, 431, 432, 433, 434, 435, 436, 437, 438, 439, 440, 441, 442, 443, 444, 445, 446, 447, 448, 449, 450, 451, 452, 453, 454, 455, 456, 457, 458, 459, 460, 461, 462, 463, 464, 465, 466, 467, 468, 469, 470, 471, 472, 473, 474, 475, 476, 477, 478, 479, 480, 481, 482, 483, 484, 485, 486, 487, 488, 489, 490, 491, 492, 493, 494, 495, 496, 497, 498, 499, 500, 501, 502, 503, 504, 505, 506, 507, 508, 509, 510, 511, 512, 513, 514, 515, 516, 517, 518, 519, 520, 521, 522, 523, 524, 525, 526, 527, 528, 529, 530, 531, 532, 533, 534, 535, 536, 537, 538, 539, 540, 541, 542, 543, 544, 545, 546, 547, 548, 549, 550, 551, 552, 553, 554, 555, 556, 557, 558, 559, 560, 561, 562, 563, 564, 565, 566, 567, 568, 569, 570, 571, 572, 573, 574, 575, 576, 577, 578, 579, 580, 581, 582, 583, 584, 585, 586, 587, 588, 589, 590, 591, 592, 593, 594, 595, 596, 597, 598, 599, 600, 601, 602, 603, 604, 605, 606, 607, 608, 609, 610, 611, 612, 613, 614, 615, 616, 617, 618, 619, 620, 621, 622, 623, 624, 625, 626, 627, 628, 629, 630, 631, 632, 633, 634, 635, 636, 637, 638, 639, 640, 641, 642, 643, 644, 645, 646, 647, 648, 649, 650, 651, 652, 653, 654, 655, 656, 657, 658, 659, 660, 661, 662, 663, 664, 665, 666, 667, 668, 669, 670, 671, 672, 673, 674, 675, 676, 677, 678, 679, 680, 681, 682, 683, 684, 685, 686, 687, 688, 689, 690, 691, 692, 693, 694, 695, 696, 697, 698, 699, 700, 701, 702, 703, 704, 705, 706, 707, 708, 709, 710, 711, 712, 713, 714, 715, 716, 717, 718, 719, 720, 721, 722, 723, 724, 725, 726, 727, 728, 729, 730, 731, 732, 733, 734, 735, 736, 737, 738, 739, 740, 741, 742, 743, 744, 745, 746, 747, 748, 749, 750, 751, 752, 753, 754, 755, 756, 757, 758, 759, 760, 761, 762, 763, 764, 765, 766, 767, 768, 769, 770, 771, 772, 773, 774, 775, 776, 777, 778, 779, 780, 781, 782, 783, 784, 785, 786, 787, 788, 789, 790, 791, 792, 793, 794, 795, 796, 797, 798, 799, 800, 801, 802, 803, 804, 805, 806, 807, 808, 809, 810, 811, 812, 813, 814, 815, 816, 817, 818, 819, 820, 821, 822, 823, 824, 825, 826, 827, 828, 829, 830, 831, 832, 833, 834, 835, 836, 837, 838, 839, 840, 841, 842, 843, 844, 845, 846, 847, 848, 849, 850, 851, 852, 853, 854, 855, 856, 857, 858, 859, 860, 861, 862, 863, 864, 865, 866, 867, 868, 869, 870, 871, 872, 873, 874, 875, 876, 877, 878, 879, 880, 881, 882, 883, 884, 885, 886, 887, 888, 889, 890, 891, 892, 893, 894, 895, 896, 897, 898, 899, 900, 901, 902, 903, 904, 905, 906, 907, 908, 909, 910, 911, 912, 913, 914, 915, 916, 917, 918, 919, 920, 921, 922, 923, 924, 925, 926, 927, 928, 929, 930, 931, 932, 933, 934, 935, 936, 937, 938, 939, 940, 941, 942, 943, 944, 945, 946, 947, 948, 949, 950, 951, 952, 953, 954, 955, 956, 957, 958, 959, 960, 961, 962, 963, 964, 965, 966, 967, 968, 969, 970, 971, 972, 973, 974, 975, 976, 977, 978, 979, 980, 981, 982, 983, 984, 985, 986, 987, 988, 989, 990, 991, 992, 993, 994, 995, 996, 997, 998, 999, 1000)

Gallium arsenide (GaAs) cell fabrication requires two major inputs: gallium and arsenic. Quantities of material inputs are shown in Table 1. Gallium is a byproduct of processing certain aluminum and zinc bearing ores; the primary source is refinement of bauxite [8]. Arsenic input is in the form of arsenic trioxide (As_2O_3) [2]. Almost all uses of arsenic are dissipative. Resources are associated with complex base-metal ores in trace quantities. Commercial production of arsenic is predominantly from processing copper ores [8].

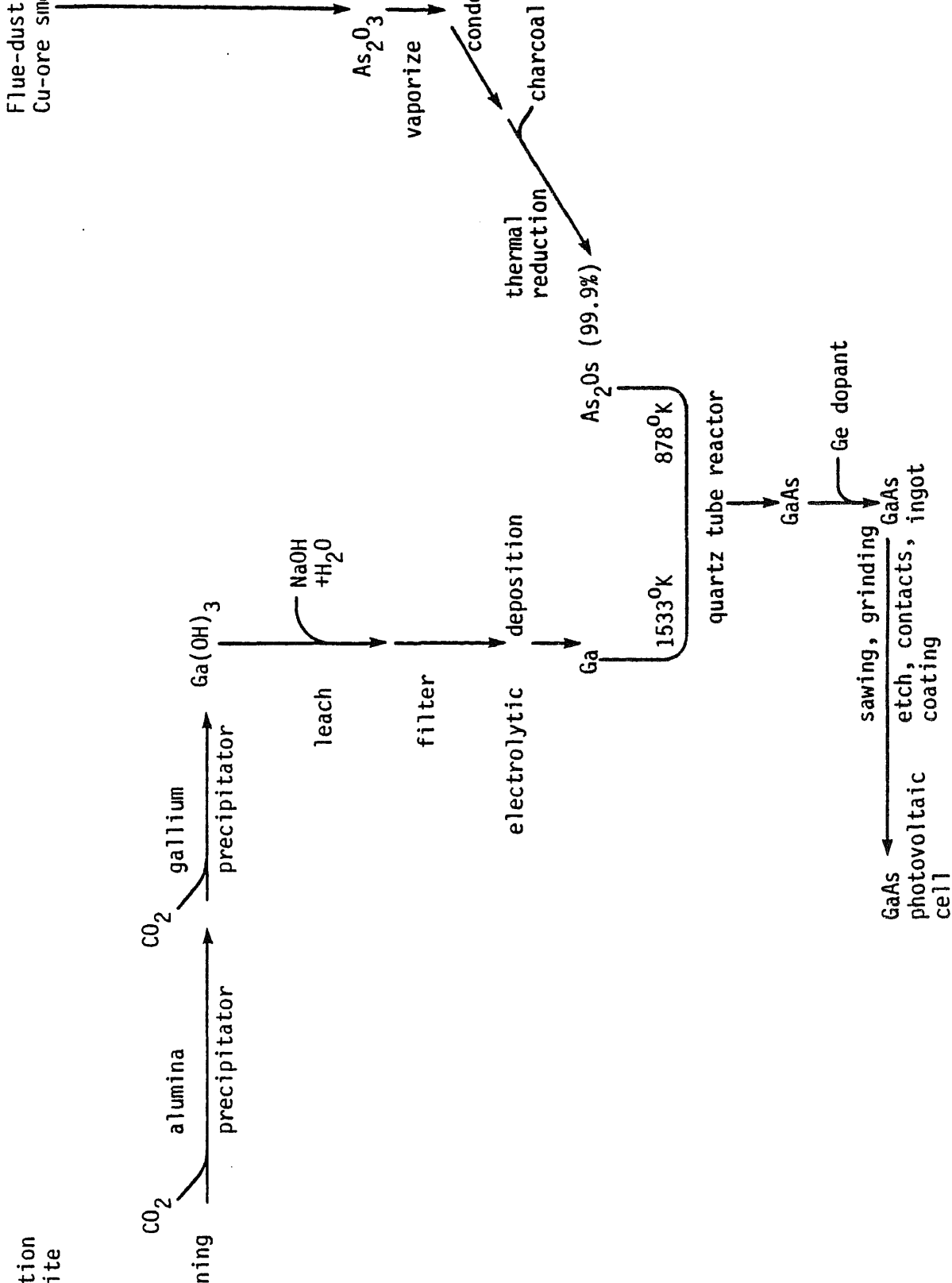
Production of GaAs cells is largely a laboratory process at present and, as such, emissions from a commercial cell production facility may differ considerably from estimates. A probable production schematic is shown in Figure 3. One source [6] states that in addition to arsenic trioxide, cell production would emit 54,430 to 108,860 MT(60,000 to 120,000 T) alumina sludge (containing trace metals) per gigawatt (GW) cells, 36 MT(40 T) sulfur dioxide per GW cells, less than one MT(1 T) lead and arsenic per GW, and unspecified amounts of mercury-containing waste water. If concentrating Fresnel lenses are used in the system, their production will release acetone, methanol, sulfuric acid, inorganic sulfate salts, and hydrogen cyanide [6]. These projected emissions are toxic; thus, release would present hazards to wildlife and humans.

3. ENVIRONMENTAL IMPACTS ON SYSTEM INSTALLATION AND OPERATION

Installation of a photovoltaic plant at the deployment site will produce impacts similar to construction of any large power production facility. All power plants will require inputs of concrete, steel, and land. Initial photovoltaic facilities will probably be built in deserts or semiarid regions with high insolation. The impacts of plant construction will depend somewhat on site selection (i.e., amount of grading necessary, required construction of access roads, local wildlife density, etc.).

Most burrowing desert species spend daytime hours underground to escape the heat. Excavation and site grading, which will be performed during daylight hours, will destroy large numbers of burrowing species. Construction activities, noise, and other activities noxious to wildlife will force emigration of mobile species and destroy many less mobile and sessile species [6, 9, 12]. Severe impacts on local desert ecosystems may be somewhat mitigable by siting photovoltaic plants in sparsely populated desert playas [12].

Land use will be significant, as summarized in Table 2. Installation of photovoltaic arrays over large areas will modify the local terrain, species composition, and meteorology. Wind and water erosion may be increased (perhaps temporarily) by removal of vegetation and destruction of the desert crust and pavement [6, 12, 13]. Shading from arrays may induce flora (and as a consequence fauna) changes by decreasing temperature and moisture evaporation [9, 12]. Destruction of vegetation and physical presence of arrays may interfere with wildlife grazing patterns [11]. Although the plant will emit no thermal pollution, large arrays may produce "heat islands" via sunlight reflection. Normal desert albedo is 25% to 30%. Shading



[14]. Large arrays may also affect wind flow in addition to changing albedo [6].

System operation will have little or no impact on local air and water quality. The array will emit no gaseous or particulate pollutants, liquid wastes, or solid wastes under normal operating conditions [2, 6]. Silicon and cadmium sulfide arrays will require only negligible amounts of water (small quantities will be required for panel cleaning) and therefore will not pollute local waterways under normal operating procedures [10]. GaAs arrays with concentrating Fresnel lenses will require water to cool and maintain panel frames at temperatures between 122°F and 212°F. Systems will probably recirculate water thereby minimizing water inputs and release potential [6, 11]. Accidents such as fire could cause release of toxic fumes from combustion of the CdS and GaAs cells, encapsulation materials, and/or concentrating lense materials [5].

Table 2. LAND REQUIREMENTS FOR PHOTOVOLTAIC CELL PLANTS*

Cell Type	Cell Efficiency, %	Land Use mi^2/GW_e
Si	2 - 10	3.4
	3 - 16	2.25
CdS/Cu ₂ S	1 - 8	4.5
GaAs	4 - 17	2.1

*Source: Reference 6.

4. SYSTEM DECOMMISSION

Once the useful life of a photovoltaic system has expired, spent cells may be replaced or the entire system decommissioned. Decommission operations will involve dismantling and salvaging or disposing of system parts, and removal of support structures. Whether spent cells are replaced or the system is dismantled, cells will have to be disposed of or recycled.

Silicon cells are amenable to either recycle or disposal. Cells can be repurified, recrystallized, and refabricated into new Si-photovoltaic cells. Conversely, cells can be crushed and landfilled. Because silicon is not toxic and is environmentally stable, landfill will present little hazard [6].

Because of their composite nature (i.e., an amorphous, cadmium sulfide-copper sulfide mixture) and low cadmium content, CdS cells are not amenable to recycle given current technology. Incineration is not an acceptable disposal option due to release of toxic cadmium fumes. Spent cells can be landfilled but only at sites not subjected to acidic drainage, [6] since the only known case of environmental cadmium poisoning resulted when acidic drainage leached cadmium from the tailings of a Japanese mine [7]. It should be noted that cadmium in nature occurs as a stable sulfide ore which is insoluble and biologically inactive [6].

Disposal and recycle methods for gallium arsenide cells have received very little research attention. Decomission of a 1 GW_e facility will require disposal or recycle of 1,700 MT(1,875 T) methacrylate polymer (from the Fresnel lenses) and 50 MT to 250 MT(55 T to 275 T) GaAs cells. No methods have yet been determined [6].

5. SUMMARY AND CONCLUSIONS

As the previous sections point out, environmental and health risks do exist within the life-cycle process for photovoltaic cells. The most hazardous phase is cell production. Research is underway or planned for the following areas (among others): (1) industrial hygiene of component manufacture; (2) the metabolic effects of cadmium; (3) the pancreatotoxic effects of cadmium; (4) study of populations in areas of cadmium refining; (5) health effects of silicon inhalation; (6) the carcinogenic effects of arsenic; (7) impact of deploying systems in desert environments; (8) release of toxic compounds during fires; and (9) cell disposal techniques [5]. Potential adverse impacts must be identified and characterized to mitigate effects and to determine advantages and disadvantages of displacing fossil fuel electricity generation technologies by electricity from photovoltaic cells.

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Introduction

Every manufacturing facility generates waste materials that must be discarded in an ecologically satisfactory manner, requiring that environmental controls be defined and implemented. Historically, the driving force for these environmental controls has been a trade-off between economics and legal requirements. Concern for the environmental and safety impacts of manufacturing effluent in air, water and solid waste have been weighed against the necessity of making a reasonable return on company investment. The solar photovoltaic industry is a relatively new and evolving industry. In such evolving industries, integration of environmental considerations during the planning phase is proving to be both economically and environmentally profitable.

The photovoltaic industry is, by its nature, a spinoff of the semiconductor industry; in fact, they most likely will be interdependent for decades to come. For that reason, the technological innovation for environmental controls that has taken place in the semiconductor industry provides the most advanced research and methodologies for environmental problem solving that can be found for the photovoltaic industry. Conversely, manufacturing developments in the emerging photovoltaic field must supply new and cost-effective innovations for the total semiconductor arena. In both cases, economics and ecology are equally important driving forces for environmental controls. The two major economic factors, consumed materials and cost avoidance, are discussed here.

The Photovoltaic and Semiconductor Industries

In the past, the semiconductor industry has developed manufacturing processes and specified materials based upon technical viability, independent of environmental concerns. Only following choice and implementation of the process or material into the manufacturing facility were environmental controls fully implemented, and then primarily through exhaust or dilution. Environmental control has, thus, historically been an "end-of-the-pipe" technique.

The photovoltaic industry today, as an outgrowth of the semiconductor industry, still utilizes this "end-of-pipe" control philosophy in established manufacturing facilities. There is, however, a major impetus to reduce the cost of photovoltaic device manufacturing. This cost reduction drive is, in turn, changing the role of environmental control planning to one of major importance during process and material selection rather than following that selection.

hand, presents only a finite amount of power on a given area. The photovoltaic more power generation requires more area of solar cells. The photovoltaic industry will require larger and larger areas, while the semiconductor industry can expand through further microminiaturization. The photovoltaic industry is, thus, far more materials cost dependent than the semiconductor industry, an important factor in considering environmental controls.

Consumed Materials

In every manufacturing operation, all manufacturing costs can be identified as being either labor costs, capital costs, or consumed materials costs. If the operation is heavily automated, the labor cost for each manufactured unit approaches zero. Further, if the automated equipment has a very high throughput, the capital cost allocated to each manufactured unit over the life of the equipment also approaches zero. The ultimate cost of the manufactured unit, thus, is determined by the cost of the materials consumed in the manufacturing operation. Ideally, all consumed materials would appear in the finished product and the manufacturing yield would be 100%. In such an ideal case, there would be no wasted materials and no scrap units requiring disposal. A broad definition of wasted material, then, is any material not incorporated in a delivered product.

Unfortunately, ideal manufacturing facilities are unlikely ever to exist. The goal of 100% materials utilization can, however, be approached through careful selection and development of suitable manufacturing process steps. The goal of these steps is to waste a minimum amount of materials. Further, each manufacturing step must be chosen such that it has an inherently high yield, implying that the cost-effective process control range of the step is inherently broad and insensitive to minor control variations.

Processes utilized today in both the photovoltaic and semiconductor industries are highly materials consumptive. A typical manufacturing sequence contains numerous wet chemistry cleaning or etching steps, gaseous diffusion steps, and metallization by vacuum evaporation. Further, some sequences may also include photolithography (photoresist) steps. These processes consume and waste large quantities of acids, solvents, gases, and water. A representative list of typical consumed materials is presented in Table 1.

The cost of safely handling and disposing of waste process materials, when added to the actual cost of the wasted materials, is very large with today's technology. The total cost is so large, in fact, that the long-range cost goals for solar photovoltaic modules of less than \$0.50/peak watt of power appears impossible with today's technology.

It is a well known fact that, in today's economy, costs of chemicals and other materials used in manufacturing solar cells do not remain stable for any period that allows projections. However, with increasingly high

Acetic Acid
Sulfuric Acid
Fluoboric Acid
Hydrogen Peroxide
Ammonium Hydroxide
Ammonium Chloride
Potassium Hydroxide
Sodium Hydroxide
Potassium Cyanide
Sodium Hypophosphite
Nickel Salts
Palladium Salts
Silver Salts
Proprietary Plating Baths
Phosphine

Silicon Tetrachloride
Trichlorosilane
Dichlorosilane
Ammonia
Hydrogen
Lead-Tin Solder
Photoresist (Xylene-based)
Ethylene Glycol
Isopropyl Alcohol
1-1-1 Trichloroethane
Butyl Acetate
Toluene
Acetone
Proprietary Solvent Mixes

environmentally.

True economic benefit can be realized through development and substitution of new processes that consume smaller amounts of materials, wasting less. There is, thus, a major driving force for the photovoltaic industry to choose processes that will consume less material than today's technology requires. This makes environmental control an automatic factor in process selection, not an afterthought.

Cost Avoidance

In the early 1970's, it was recognized at Motorola that a new approach to addressing environmental needs was required. This has led to the development of a "cost-avoidance" theory which has since gained broad acceptance.

It is difficult for industries to justify implementation of costly environmental controls that will not directly result in an identifiable return on investment on the balance sheets. Recognizing this, cost avoidance theory provides another accounting method that can be used for showing how environmental expenditures will return a "profit" in the future. Weighed against the alternatives of waiting until future regulations demand that a clean-up technology be installed or a plant be closed down, the cost avoidance can be considerable. Of course, a plant shut-down condition is the extreme case. What must occur is the application of cost avoidance theory for environmental controls in the planning phase of the decision making process, where a new operation or a new manufacturing area is being designed.

In the semiconductor industry, and no less so in the photovoltaic industry, it is when plant modification or expansion is planned that crucial decisions can be effectively integrated so that environmental and health concerns become a part of the final implementation. Unless there is a management commitment early, however, this portion of the planning process can be negated by economic forecasting that precludes cost-avoidance as a variable; it is, after all, a tool not taught in classical business management courses.

A typical example of how cost avoidance theory has been applied was in the use of trichloroethylene (TCE), a commonly used degreasing solvent in the semiconductor industry. TCE is photochemically reactive and now known to be carcinogenic. In 1973, Motorola Semiconductor Division environmental engineers initiated a study to determine how much TCE was being used, costs of replacing it with another solvent (at that time, unproven and untried), and the overall economic impact to the company of such action.

Initially, upper management was made aware that the future for photochemically reactive solvents would be questionable. A survey involving federal, state and local regulatory officials was initiated to determine

ical(s) must have less (or ideally no) environmental impact, be reasonably cost-similar to TCE, and have no known side effects on health. These were high ideals, indeed, but necessary if the program were to be successful.

By mid-1974, research had confirmed that use of 1-1-1 Trichloroethane, alone in some cases or in combination with dry plasma technology in other cases, could virtually eliminate the need for TCE in our semiconductor manufacturing facilities. 1-1-1 Trichloroethane, first of all, is not photochemically reactive; in addition, research by various government bodies was being published at about the same time that showed that TCE was carcinogenic while 1-1-1 Trichloroethane had, thus far, been cleared of that possibility. Finally, use of 1-1-1 Trichloroethane was shown to be very effective as a substitute degreasing agent in areas where TCE was used.

In terms of cost avoidance, our most conservative estimate had predicted that we would evaporate (and thus exhaust) thousands of pounds of TCE into the atmosphere each month from over 25 exhaust systems. Engineering solutions for photochemically reactive air emissions require unproven end-of-pipe environmental control technology such as thermal incineration or carbon adsorption, neither of which offer efficient removal techniques, and both of which are costly in maintenance after installation. Even if a majority of TCE exhausting systems could have been centralized (a truly unworkable theory in a plant spread out over 80 acres, 15 major buildings, and 1.5 million square feet), the total dollar cost of either incineration or adsorption would have been over \$2 million, not including costs of combining exhaust systems, production down-time and long-term maintenance.

At about the same time, this country was entering the Arab oil embargo. Word was received from chemical manufacturers that TCE would be in shorter supply in future months. That provided the final incentive to begin using the alternative solvents and technology that our research had predicted would achieve results.

In summary, no TCE is used today in any of our semiconductor facilities. The cost avoidance program showed a savings of over \$2 million and no production time was lost in changing.

The key ingredients in this example were the integration of environmental controls (i.e., cost avoidance planning) in the early stages of evaluating an impending problem as well as thoroughly investigating alternative technology that could be used to eliminate an offending chemical. Thus, when photovoltaic solar cell manufacturing was being planned, the history of the TCE problem was automatically included by management and as a result no TCE is used.

EXAMPLES OF MAJOR PROCESSING CHANGES

1. Dry Plasma to Replace Wet Cleans and Etches
2. Ion Implantation to Replace Gaseous Diffusion
3. Mechanically Masked Plasma to Replace Photoresist
4. Plating to Replace Evaporation

TABLE III

FUTURE MATERIALS LIST

Silicon Etch:	Sodium Hydroxide Producing Silicates
Ion Implantation:	Phosphine, Boron Trifluoride
Silicon Nitride:	Ammonia, Dichlorosilane
Pattern:	Freon (CF_4)
Metal:	Palladium and Nickel Plating Baths
Encapsulate:	Glass, Pottant, Silicate (Reclaimed from Above Treatment)

technique is firmly incorporated into Motorola's planning in the photovoltaic technology advancement necessary for a major future industry.

Consumed Material and Cost Avoidance Theories for Environmental Controls in the Photovoltaic Industry

As previously noted, Table I is a partial list of chemicals that have been used in the manufacture of photovoltaic solar cells. Examining these from an environmental perspective, it can be seen that use and disposal of many of these materials will impact wastewater, air, and solid waste, thereby requiring controls to reduce or negate the impact on the environment. This is especially significant when utilizing the classical approaches to solving such industrial pollution problems with "end-of-pipe" controls. Until recently, emphasis was placed on unlimited processing and manufacturing flexibility. This philosophy basically allowed unlimited selection of processing technology, materials, chemicals and manufacturing methodology in an effort to realize an advancement in technology. Such a philosophy, however, also requires that health and environmental controls, where required, must be instituted as retrofit items and not as an integrated part of the process and manufacturing design.

The present photovoltaic industry is small and has limited cost-effective applications. Major cost reductions over present photovoltaic technology must be achieved to establish photovoltaics as a major energy supplier. Incorporating the minimization of consumed materials and the cost avoidance concepts, incentive exists to modify or replace the wasteful materials and processes now used. Such efforts are underway throughout the industry. In almost all cases, alternative process steps have been identified which satisfy both concepts. In other cases, decisions which utilize environmental concerns as a major process selection criterion are now underway.

Examples of potential major processing changes are shown in Table II. In all cases, major reduction, in both the numbers and quantities of chemicals utilized in the processes (and wasted), are achieved.

A typical materials list that could result from implementation of these processes is shown in Table III. Contrasted with those of Table I, it can be seen that a considerable potential for reduction in environmental impact of the resulting effluent exists. Coupled with this positive gain is a reduction of cost benefit, as well as a commitment to future processing technology which has built-in environmental cost avoidance by virtue of reducing the necessity for exotic wastewater, air, and solid waste technology. As stated before, this has not occurred accidentally. Furthermore, the list contained in Table III, with proper planning and integrated environmental controls emphasis, may be further reduced in the future as newer technology becomes available.

Summary and Conclusions

It is clear that end-of-pipe environmental control represents a costly, and inefficient method of solving environmental problems. Since photovoltaic technology is materials intensive, it is apparent that reduction or elimination of environmentally unacceptable materials and processes is a priority that must be established early. In minimizing materials consumed and wasted, maximizing recycling of chemicals, and substituting less toxic chemicals and processing materials for those that are environmentally unacceptable, worker protection can be achieved, environmental and safety concerns can be satisfied, and the economic growth rate of the entire photovoltaic industry can be enhanced. Technology expertise in the semiconductor industry can aid in the necessary efforts to achieve these goals.

Ecology and economics are coincident driving forces: economics demands minimum materials consumption and ecology demands minimum waste. In the future of the photovoltaic industry, these driving forces are complementary, resulting in newer and more efficient processes, recycling of consumables, and increased advanced planning for environmental controls. The result will be an economically driven major growth industry that is, thus, necessarily environmentally clean.

I. BACKGROUND

The statement that "there is nothing new under the sun" seems particularly appropriate when considering solar thermal electric power generation. Many solar thermal systems were built and used in the late 1800's and early 1900's. One hundred years ago a solar steam engine was demonstrated in Paris. Only fifty years ago a similar engine was used to pump water into a reservoir. The water, when released, drove a turbine to produce electricity to illuminate a mine. Development of such innovations was aborted by the perfection of the internal combustion engine, the availability of very cheap fuels, and the consequent advent of low cost electricity. Today, a short fifty years later, following incredible socioeconomic impacts, the cheap fuels are in short supply. Our appetite for electric power, however, whetted by the unlimited low cost electricity of the past, continues to grow. Solar Thermal Power Systems (STPS) are among the technologies that might satisfy that appetite. Fortunately much of the basic STPS technology is already in hand. The question we face now is not whether electric power can be generated from solar thermal technology, but rather, to what extent STPS can replace reliance on conventional oil and gas fired electric power generating systems? Most of the answer is deeply rooted in economics, but a part of the answer depends as well on whether commercialization of STPS will introduce costly environmental issues.

The DOE defines "environmental" to include occupational and public health and safety, socioeconomics, legal, and ecological factors and mitigating measures (1). Even within such a broad context STPS appears as a benign technology because it is based upon use of an inexhaustible and virtually free fuel unencumbered by delivery problems, which produces minimal impacts on air quality when consumed, and leaves no ash. In addition, except for the method of collecting and storing thermal energy, STPS consist largely of subsystems common to conventional power plants. The environmental consequences of boilers, turbines, electric generators, cooling towers, and transmission lines are familiar...at least in a generic sense...and do not appear disqualifying. Never-the-less there are environmental concerns which must be addressed. Whether the "concerns" are truly "issues" may depend more on personal weighting than available data at this time.

Identification of environmental concerns is somewhat confounded by the versatility of STPS technology which consists of several innovative ways of collecting solar thermal energy which can be matched to a variety of energy conversion systems, which in turn can be sited in full spectrum of environmental settings, vary in capacity from a few MWe to several hundred MWe, and be designed for base-load or intermittent use. When assessed within the broad context of DOE environmental categories an enormous list of environmental concerns can be compiled; each concern with its protagonist and

II. STPS SUBSYSTEMS AND ASSOCIATED ENVIRONMENTAL CONCERNS

"In principle solar thermal power systems utilize solar radiation to heat a working fluid to a temperature high enough to power a turbine. The turbine's mechanical output can be used to drive an electric power generator which produces electricity" (2). Two applications are envisaged. Central Power systems would utilize solar power plants of relatively large capacity (20 MWe or greater), be designed for use in utility networks, and probably be sited in remote locations. Dispersed Power systems, on the other hand, would generally employ solar power plants of lesser capacity and characteristically would be located in close proximity to the point of energy use. It should be useful to briefly review the STPS subsystems to indicate where environmental concerns originate.

Collector/Concentrator Subsystem

"The collector/concentrator subsystem has as its basic function the interception, concentration and delivery of direct solar radiation to the receiver/heat transfer subsystem. This subsystem consists of a field of concentrating lenses or mirrors to focus the sun upon the receiver. There are two basic distributed receiver collector categories: point focusing and line focusing. The parabolic dish focuses on an absorber at the focal point of the dish. The parabolic trough collector focuses on a long receiver tube and is an example of a line focusing concept (Figure 1B). The heliostat/central receiver ("power tower") concept (Figure 1A) is also a point focusing system" (2).

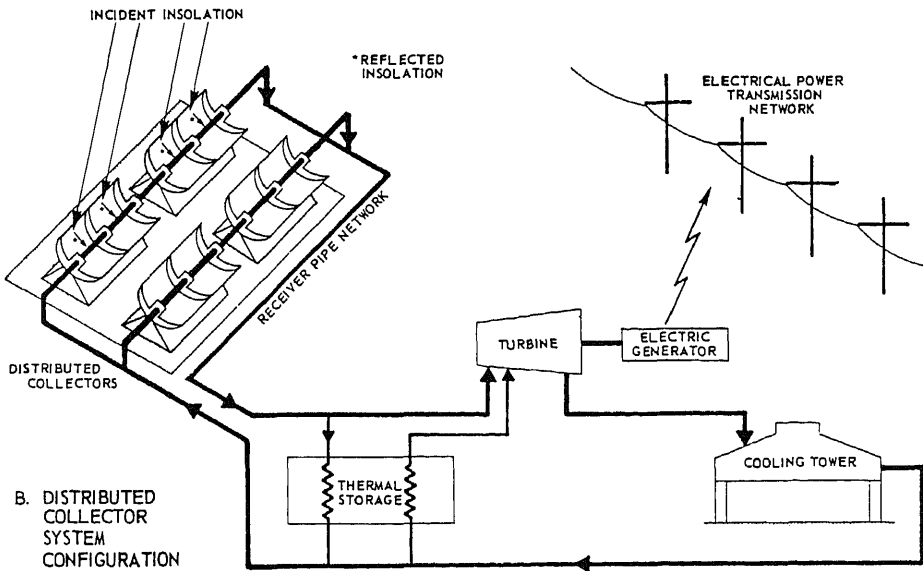
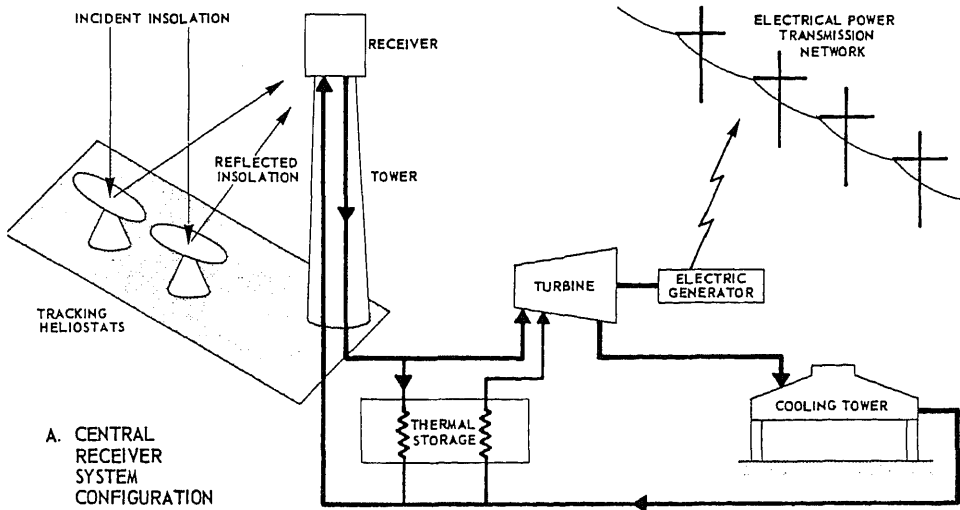
The technology is inherently land intensive because solar insolation is low, and at present thermal conversion efficiency of the total system is low. It has been estimated that approximately 1 km² of mirror area or 2 km² of land area would be required to supply 100 MWe of intermediate load power (3, 4). A base-load power plant could require twice as much area.

It is reasonable to expect that early commercialization of large scale STPS will occur in deserts of the southwestern U.S. because the technology is land intensive and benefits from high levels of insolation. Three environmental concerns are coupled to the collector/concentrator subsystem: (1) Land-use; (2) Effects of misdirected reflections; (3) Fate of liquids used to clean heliostats; and for large scale central STPS (4) Ecological and microclimatic effects; and (5) Socioeconomic impacts.

Receiver/Heat Transport Subsystem

"This subsystem collects the redirected solar radiation from the heliostats or collectors and transfers the solar energy to the working fluid. The fluid is then pumped to a heat engine or thermal storage subsystem. The receiver/heat transport subsystem consists of a receiver support structure, the receiver, pumps, heat exchangers, and a working fluid. Working fluids in the heat transfer subsystem which are used to transfer energy from the receiver to the heat engine or thermal storage subsystem are typically water, molten salts, or synthetic oils." (2)

FIGURE 1
SOLAR THERMAL POWER SYSTEM CONFIGURATION (5)



The environmental concerns coupled to this subsystem are (1) Handling and disposal of system fluids and wastes; and (2) Consequences and mitigation of accidental releases of working fluids both on-site and off-site. Worker safety on-site, and public safety and ecological effects off-site are the primary focuses of these concerns.

Heat Engine Subsystem

"The heat engine subsystem links solar thermal conversion subsystems with conventional electric power generating technologies. The heat engine transforms thermal energy from the receiver/heat transport subsystem into useful energy to drive a conventional generator."

"Heat engines utilizing Rankine, Stirling and Brayton cycle principles are under investigation. The Rankine cycle uses vaporized fluids, such as water to power a turbine. The Brayton cycle such as used in conventional jet aircraft engines, uses gas such as air as a working fluid. The Stirling cycle uses gases, such as hydrogen or helium as a working fluid" (2).

At the present stage of development solar thermal power plants may require somewhat more cooling water than conventional systems because of their lower thermal energy conversion efficiency. For example, an oil-fired power plant using a Rankine cycle heat engine, generating 1000 MWe, and operating at an efficiency of about 34% may use 12,000 to 15,000 acre feet per year of cooling water. An equivalent solar plant would require 20,000 to 25,000 acre feet per year and would operate at less than 20% efficiency (6). The planned 10 MWe pilot plant located near Barstow, California is anticipated to use 220 acre feet per year (7). On the one hand, water requirements could be substantially more if a once through cooling system is required because of poor water quality. On the other hand "dry" cooling towers could be used to reduce water consumption but that would entail higher costs and even greater loss in plant efficiency (8). Open Brayton cycle heat engines require essentially no cooling water, but the engine is still under development.

The environmental concerns coupled to this subsystem tend to be site specific. They are (1) Availability of cooling water for large scale central STPS; and (2) Effects on local ecosystems of cooling tower drift.

Thermal Storage Subsystem

"This subsystem stores thermal energy generated by collectors and receivers in excess of that required for immediate operation. Stored thermal energy is used to generate electric energy during periods of time when direct solar radiation is not available."

"Thermal storage technology employs either the sensible heat or latent heat-of-fusion properties of various storage media. Examples of sensible heat storage media include oils, molten salts, and combinations of rock or oil; while latent storage involves freeze-thaw characteristics of selected materials such as molten sodium hydroxide or potassium hydroxide" (2).

"These subsystems perform a wide range of functions associated with operation of a solar thermal power system, from specialized tasks such as heliostat tracking to control of an integrated plant's operation. The control system is composed of a computer, sensors, and control drive elements" (2).

This subsystem is included for completeness. There do not appear to be environmental concerns specific to Control Subsystems.

III. ENVIRONMENTAL CONCERNS

We can summarize as follows before addressing specific environmental concerns. At the present state of development large scale centralized STPS are land, water, and capital intensive. Early commercialization will probably occur in relatively remote undeveloped desert areas. That is not to say that commercialization cannot occur at any site where the level of insolation is acceptable. The principal environmental concerns are for worker safety on-site and for ecological impacts in the vicinity of STPS sites. The primary siting constraint may be availability of water.

Smaller scale dispersed systems are likely to be located near areas already developed for agriculture or industry. The primary environmental concern will be public safety and protection of property. The primary siting constraint may be institutional barriers associated with land use, zoning and utilities interfaces.

A. Land Use

It is probable that early commercialization of central STPS will occur in the desert regions of the southwestern U.S. These areas are frequently looked upon as non-productive wastelands less sensitive to environmental disturbance than other areas and consequently prime candidates for power plant siting. Whether or not these desert sites represent wastelands is equivocal. In general the environmentalists and ecologists protest that such environments are unique and the plants and animals which occupy the desert are highly specialized members of a particularly fragile ecosystem. In addition, greater numbers of people have begun to use the desert as a recreational area and pressure has increased to maintain the aesthetic state unique to the desert. The Bureau of Land Management is currently developing a desert management plan in response to such interest which, when completed, may restrict STPS site selection.

To the extent that sites for early large scale centralized STPS are limited to southwestern deserts, site selection must be acknowledged as a potential problem that may impact both rate and cost of exploitation. Land

reflections. Plant size may need to be increased. Rather than increasing factors for utility baseload operations are used. However, it has been suggested that a hybrid the size of the solar plant, however, it has been suggested that a hybrid fossil-solar system be developed in which fossil fuel combustion drives the turbine when the solar portion of the plant is not functioning. The land requirements remain very large. A recent economic study indicates that such hybrid systems may be a poor match because both technologies are so capital intensive (9). Desert lands are extensive but not unbounded. Many convenient large tracts of land with usable water may not be available or transmission line corridors may be restricted. The bureau of Land Management is currently developing a desert management plan which includes identification of areas for protection under the National Wilderness Protection Act. Military reservations, Indian lands, and railroad right-of-ways further partition the apparent continuous desert expenses. This is not to say that land is not available. One study estimates that there are about 5000 mi² of desert in California alone suitable, and presumably available, for very large central STPS (4). That estimate, however, was made without regard to available water.

B. Water Use

Solar thermal power plants may require more water than conventional systems because of their lower thermal energy conversion efficiency. If we continue with our premise that early large scale central STPS will be sited in the southwest, then the difference in water requirement between solar and conventional technologies is academic since all water is in short supply. All known and accessible water in the west is fully allocated and water delivery costs are underpriced (10). It may be necessary to purchase small parcels of land to secure water rights, but whether the water obtained can be freely used may be subject to litigation. Most water allocations have been made within the context of agricultural use. Water drawn from an area is generally expected to be returned by irrigation and run-off. In the case of "wet" cooling towers and evaporation ponds, the water is evaporated and thus represents a greater net loss to the local water supply than agricultural use.

Water drawn from rivers for "once-through" cooling is also in limited supply and carries with it significant costs in water quality maintenance (6, 10). The limiting factor to siting STPS in the desert appears to be the very trait which makes the area a desert--lack of water. Ingenious ways of meeting water requirements are being explored such as reuse of agricultural runoff, development of "dry" cooling towers, desalination of water unfit for other uses, and mining water from ancient aquifers.

Water use is not an environmental concern that should block commercialization of STPS. Other power generation systems require water as well. Water availability, however, can represent a significant siting constraint in arid regions of the Southwestern United States. As one considers smaller plants sited in less arid regions the concern over water availability becomes less important.

significantly in case of accident or improper fluid management. Fugitive dust may be a problem during construction but will need to be controlled after plant commissioning to prevent deterioration of heliostat surfaces.

There is a possibility that the high temperatures and light intensities produced at the receivers may initiate chemical reactions in the atmosphere to generate harmful pollutants such as nitrogen oxides from oxygen and nitrogen (5). STPS receivers located in areas with poor ambient air quality might produce a variety of other pollutants.

D. Microclimatic Effects

Large central STPS will cause local changes in patterns of absorption of solar radiation and thermal albedo. These will probably be accompanied by changes in air flow which will be further modified by the heliostat arrays. The magnitude of these changes will be closely coupled to the facility design and the management strategy applied to the ground surface in the heliostat field. These variables plus disturbances caused by construction activities, such as fugitive dust, may have effects on adjacent ecosystems. Modeling has been done which predicts reduction in soil surface temperatures, reduced evapotranspiration, and shading within the heliostat field. Air flow changes across the heliostat field are likened to changes caused by a forest with clearly defined borders (11).

A question yet to be resolved is how to manage the soil-surface within the site dedicated to power production. Conceivably the surface should be revegetated rather than paved. Decisions on how to manage the surface may be determined by requirements for cleaning the mirror surfaces. If simply washed with water the runoff could be used for irrigation. If a toxic cleaning solution is used quite a different problem arises which could preclude planting. The problem is being addressed in conjunction with development of the 10 MWe pilot STPS near Barstow, California.

Ecological effects adjacent to the STPS that might result from on-site microclimatic changes are difficult to project but will probably reflect effects produced by the mirror field and cooling tower and be restricted to a relatively small peripheral area.

E. Ecological Effects

For the purpose of this paper the term "ecology" is restricted to apply to natural plant and animal communities and their interaction with the abiotic environment. In this context, ecological effects of small scale dispersed STPS are considered insignificant since such facilities will probably be located in or near areas already developed.

Early commercialization of large scale centralized STPS will probably occur in relatively undisturbed and possibly remote desert areas. While some may argue that the primal desert should be preserved it is a fact

extent of these changes, however, and their impact on human affairs is speculative.

Perhaps the most sobering observation is that desert ecosystems are poorly understood. This places the environmentalist in the vulnerable position of identifying potential problems based on premises that may require many years to verify. Requirements for decisions, however, are immediate and challenges based on speculation carry little weight. The decision makers consequently are placed in no less a vulnerable position.

What is known supports the contention that desert ecosystems are extremely fragile. Plants and animals living in the desert are characterized by adaptations to limited water supply and drought and, to a lesser degree, tolerance to heat and high salt-content nutrition. The number of species within a given community tends to be small with the annual productivity of an area frequently dominated by one or two perennial species. As a consequence, animals present are closely coupled to those plant species to the extent that energy flow through the ecosystem is approximated, in some cases, by a simple "food chain" rather than a more complex "food web." It is the relative simplicity of these energy relationships which makes the desert ecosystem so fragile. A single broken link can have a profound effect which can be perpetuated for many years because of the low productivity of the desert.

It is pertinent to note that productivity in desert ecosystems is almost entirely dependent on a delicately balanced water budget. If water is drawn from the vicinity of the STPS to meet cooling requirements it would not be surprising to find such a draft reflected in the local ecosystem, if that water is evaporated from a cooling tower rather than returned to the soil via irrigation.

In general, development of a large scale centralized STPS site will certainly destroy the ecosystem on and immediately adjacent to the site, and disrupt erosion resistant soil surfaces (3, 12). That loss is probably unavoidable at a location dedicated to power production. However, ecological changes that might occur away from the site, as a consequence of STPS operations, are particularly important in desert environments where disruptions can be either irreparable or very long lasting. Serious ecological effects, if they occur, are more likely to be related to support functions common to many power generating technologies than specific to STPS. For example, the ecological effects of cooling towers, transmission line corridors, access and service roads, and construction towns are well known and acute in desert environments (10, 12). In fact recreational use of service roads for access to remote desert locations characteristically has impacted areas many times the size of the site the road was intended to service (13).

Accidental or emergency release of the fluids could cause fire, explosions, contamination of surface and ground water, and impact both aquatic and terrestrial ecosystems (11). Normal system flushing represents similar threats and introduces a problem of waste disposal. The fluids of concern and the consequence of their release are dependent on whether the facility is centralized or dispersed, and the nature of the ecosystem impacted. Projections of ecological effects of accidental fluid release vary from disastrous to inconsequential depending on what assumptions are made regarding the volume and composition of fluids.

It should be noted that "Water Quality Standards" are the predominant controlling regulations for operations of STPS installations. Taken in conjunction with the "Toxic Substances Act" all fluids may require collection and disposal at approved sites. Under such regulations fluid releases to the neighboring area normally would occur only from accident or catastrophe.

The consequences of fluid releases from smaller dispersed systems are not known. They could be serious because of proximity to commercial developments.

. Misdirected Solar Radiation

Misalignment of heliostats during operation, or accidental reflections of solar radiation from heliostats during installation, are serious hazards to workers in centralized STPS. A lesser but significant hazard is also associated with dispersed STPS. Consequences of misdirected solar radiation range from fire, to bodily harm, to glare in off-site areas. Considerable research has already been done concerning optical effects and safety procedures for heliostat alignment during power plant operations (11). Off-site problems associated with misdirected reflections appear to be limited to glare. The seriousness is dependent on plant design and consequent focal length. Whether glare will effect animal behavior off-site is uncertain. An exclusion area around the site may be desirable to reduce the public nuisance aspect of glare and thereby increase land requirements.

. Community Utilization of STPS

Large scale centralized STPS may prove impractical. However, smaller dispersed systems appear to have a wide range of applications. The location of dispersed STPS are likely to be near urban, industrial, and agricultural areas. Integrating STPS technology into the social and institutional constraint requires resolution of such issues as land use, sun rights, zoning, and consumer/utility interfaces. These issues should be addressed prior to the availability of the technology to enhance its utilization.

The environmental concerns discussed above do not represent the full list of concerns. For example, attention must also be given to identifying materials and manpower requirements, quantifying the environmental effects of mining and manufacturing activities, quantifying impacts of auxiliary power systems, and evaluating the full range of socioeconomic issues ranging from quality of life to cost of electric power. No significance is implied by the order in which the concerns are listed, or whether they occur as a major entry or a mention. Rather they must all be addressed and until more information is available, which is more important is speculative.

All of the concerns identified are judged to be real, partly because of lack of observational data or operational experience with the technology, and partly because elements of the technology have a history of high risk. The hazardous nature of proposed working and thermal storage fluids is recognized. The hazard of misdirected radiation from heliostats has already been experienced. With regard to on-site operations, both are occupational hazards where risks can be greatly mitigated by definition of, and compliance with, safety standards and procedures, many of which are already known.

The consequence to the off-site area bordering an STPS facility of normal glare, misdirected reflections, controlled or accidental fluid releases, normal run-off, lowering water tables, or microclimatic changes is uncertain. In all cases the environmental risk of proceeding with technology development is low. It is likely that if significant effects are found they can be mitigated, or they will represent a siting constraint rather than a technological barrier.

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INTRODUCTION

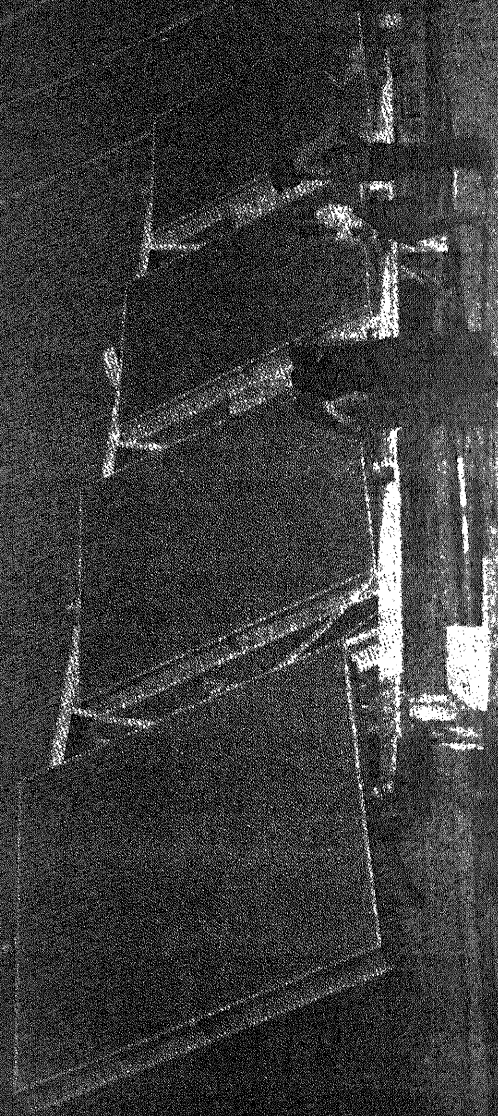
During early studies of Solar Central Receiver Power Plants in 1974-75, it was recognized that concentrated light reflected from heliostat arrays might pose a hazard for persons at ground level within or beyond the boundaries of the field, in the vicinity of the receiver at the top of the tower, or above the field in overflying aircraft. The first investigations of these potential hazards were started in late 1975 in conjunction with preliminary design activities for the 5 MW_t Solar Thermal Test Facility (STTF) at Sandia Laboratories, Albuquerque, New Mexico. This work included (1) analytical characterization of single and multiple beam flux density as a function of distance for a range of heliostat focal lengths, (2) a literature search and a discussion of retinal damage thresholds, (3) single and multiple beam retinal irradiance and image size relative to maximum safe levels, (4) beam control techniques, and (5) other higher threshold potential hazards such as skin burn and ignition of combustible materials. Results were published in May 1977 (Reference 1).

Initial investigations indicated that special beam control measures were warranted to minimize the altitude above which reflected light might pose a hazard to overflying aircraft. In the control strategy which was incorporated, beams are controlled in groups such that they always converge toward a point and diverge beyond; this drastically limited the number of beams which could be coincident beyond the aim point and greatly reduced the flux which could be produced at aircraft altitudes. At normal minimum flight altitudes, no more than one heliostat reflection (or portions of adjacent heliostats) could thus be seen at any one time.

A series of experimental measurements were also recommended to confirm analytical models and to check exposure levels under various operational modes. Such measurements were started in 1977 soon after installation of the first group of heliostats at STTF. Techniques were developed for measuring image sizes and irradiance levels relative to safe exposure limits for the human retina. Measurements of multiple coincident beams were made by means of helicopter flights over the STTF heliostat array. Single beam measurements were made of four different prototype heliostats at Sandia, Livermore in addition to the STTF design. The main purpose of this report is to describe these experiments and to summarize the results.

HELIOSTAT CHARACTERISTICS

The four heliostats evaluated at SLL are first generation subsystem research experiment prototypes, and they differ considerably in design (see Figure 1).



measurements were repeated.

The Martin Marietta heliostat is made up of 9 dished, second-surface, silvered glass facets canted to superimpose their beams at 366m (1200 ft). An AZ-EI mount arrangement is used, and the total mirror area is 41 m². At the time of first measurements, only 2 of the 9 facets were installed. Tests were repeated in July 1978 with 9 new 3mm low iron float glass facets in place. Reflectivity was about 0.89.

The Honeywell design is made up of four 3 x 3m dished, 3mm second-surface silvered glass facets canted to focus at 366m. The facets provide a total of 37.2 m² and are mechanically linked in a tilt-tilt mount arrangement. Reflectivity was about 0.87.

The Boeing heliostat utilizes an aluminized milar film mirror tensioned over a 4.57m diameter hoop. The lightweight mirror and AZ-EI drive structure is protected from the environment by a 5.18m diameter, 0.1mm thick, polished tedlar, air-supported, spherical enclosure. Total mirror area is 16.4 m². Overall reflectivity of this unit, including two-way transmission losses through the enclosure is about 0.67. Although the mirror is nominally planar, a slight amount of gravity focusing occurs depending on orientation.

The STTF heliostat design utilizes 25 1.22 x 1.22m second-surface 3mm float glass mirrors arranged on an AZ-EI mount (Figure 2). Facets are individually focused and aligned to provide a minimum heliostat beam diameter at the aim point. The particular heliostat used for the single beam measurements was focused for 100m. The full field is comprised of 222 heliostats, but at the time of the flyover tests in July 77, only the first 78 were in place. Reflectivity is about 0.83.

SINGLE BEAM MEASUREMENTS

In the process of these investigations, certain specialized techniques were developed or adapted to characterize retinal image size and irradiance relative to safe levels. It was of course not practical to make direct measurements of irradiance on the retina, so some type of indirect technique was required. Several methods were initially considered, involving the use of photographs, photometers, radiometers, calorimeters, and movie or video cameras. To obtain quantitative data on retinal exposure, a method was devised which used single frame photographic negatives in conjunction with special image analysis comparative techniques. Movie and video cameras were used to gather qualitative data on the general characteristics of multiple reflections as viewed from the airspace above the STTF heliostat field.

Stationary, ground-level measurements were first made in the beam of a single heliostat at STTF to check out experimental techniques. A 35mm Nikon Model F camera was used with a motor-driven Nikon 50-300mm zoom lens, a 3.0 inconel and a 1.0 neutral density filter, and Kodak Plus-x Pan film. The initial measurements at SLL in November 1977 were made using the same optical system. A

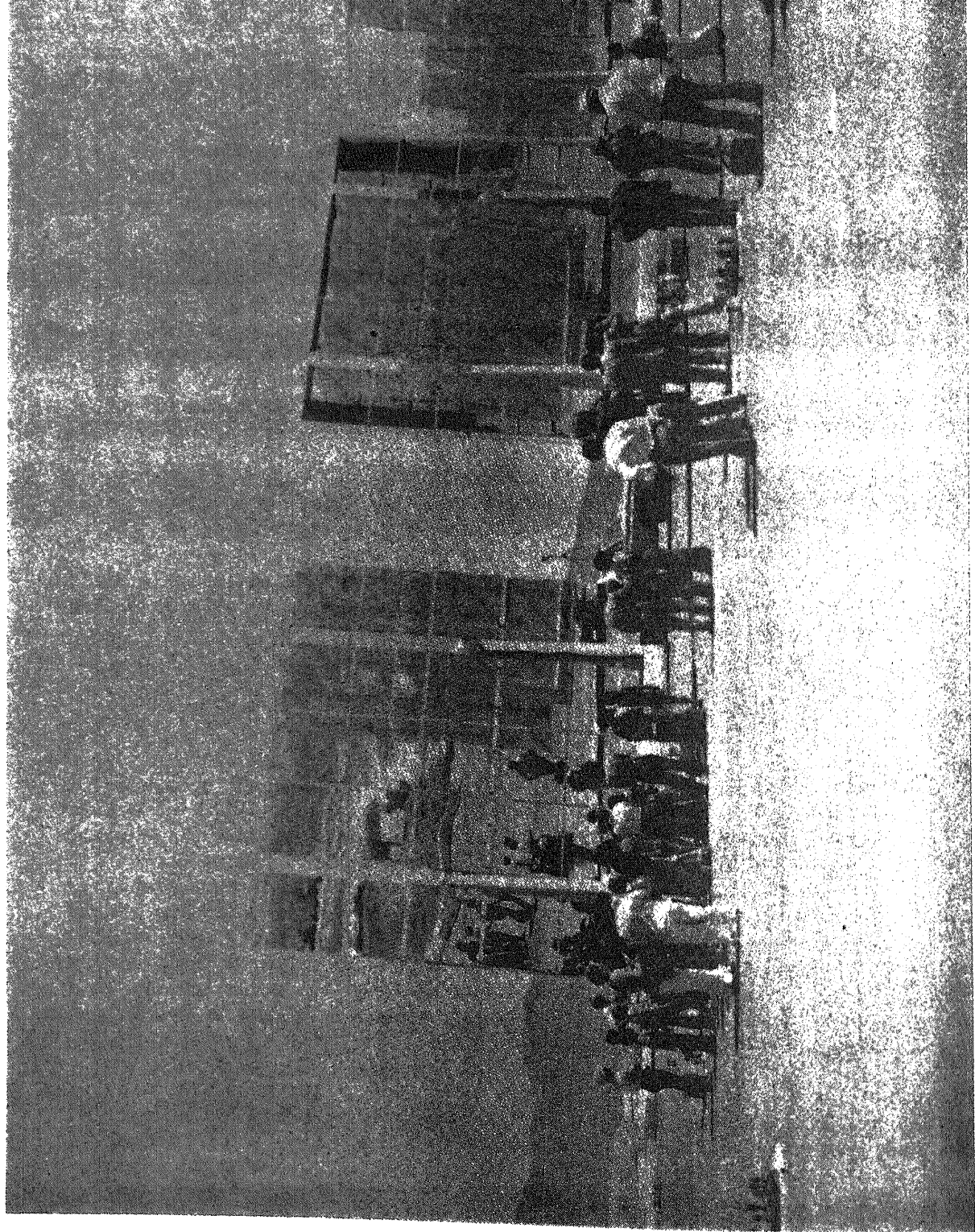


Figure 2. Select chemical waste facilities, Holston, Tennessee.

heliostat. Next, the heliostat beam was centered on the camera, and one or more exposures were taken. The camera was then moved to the next distance and the process repeated. At least one reference shot of the sun was made on each film trip -- normally one at the beginning and one at the end. If insolation was varying, a reference sun shot was made at each station immediately before or after the heliostat photograph.

The exposed film strips were developed to $\gamma \approx 0.7$ taking appropriate care to minimize non-uniformities. The finished negatives were then analyzed by means of two different methods. Each heliostat image was first scanned by an Optonics Specscan Model 3000 microdensitometer to determine peak exposure intensity relative to the peak for its reference sun image.

The second method involved the use of an image analysis system at SLL to determine relative image size and irradiance in the following way. The appropriate sun-reference negative is positioned on a light table and viewed by a Vidicon TV camera. The video output is routed to an ISI VP-8 image analyzer where two types of displays are derived. The first is an isometric projection of the image on a CRT monitor where the third dimension (contour height) is proportional to image intensity. An example is shown in Figure 3.

The second display is a color-enhanced rendition of the image on a color CRT monitor where each of six colors represents a selected range of intensity. Both types of CRT displays were photographed with a 35mm camera. An example of an STTF heliostat image is shown in Figure 4; the color enhancement is of course not evident in this black-and-white reproduction.* For these evaluations the system was adjusted so that each band represented a 16.7 percent intensity range, where 100 percent corresponds to peak intensity at the center of the reference sun image. A digital readout of the relative area occupied by each color is also provided by the system. This capability was used to obtain the relative image power of each heliostat by summing the area-intensity products for the six colors and dividing by the image power of the reference sun obtained in the same way. The relative image area for each heliostat was derived by totaling the areas of all six colors and dividing by the area of the reference sun image.

Because of the optical similarities between the human eye and photographic or video processes, these experimental measurements can be related to the retinal exposure which would be produced by direct viewing of the sun. As discussed in detail in Reference 1, a direct glance at the sun on a very clear day with a daylight adapted eye produces an image on the retina about 0.158mm in diameter with an average irradiance of about 8.5 W/cm². Thus, these sun-related measurements of heliostat images obtained via the camera can be converted to corresponding quantitative values for image area and irradiance on the retina of the human eye. By making a conservative, simplifying assumption that the

*The full series of color slides were shown at the symposium.

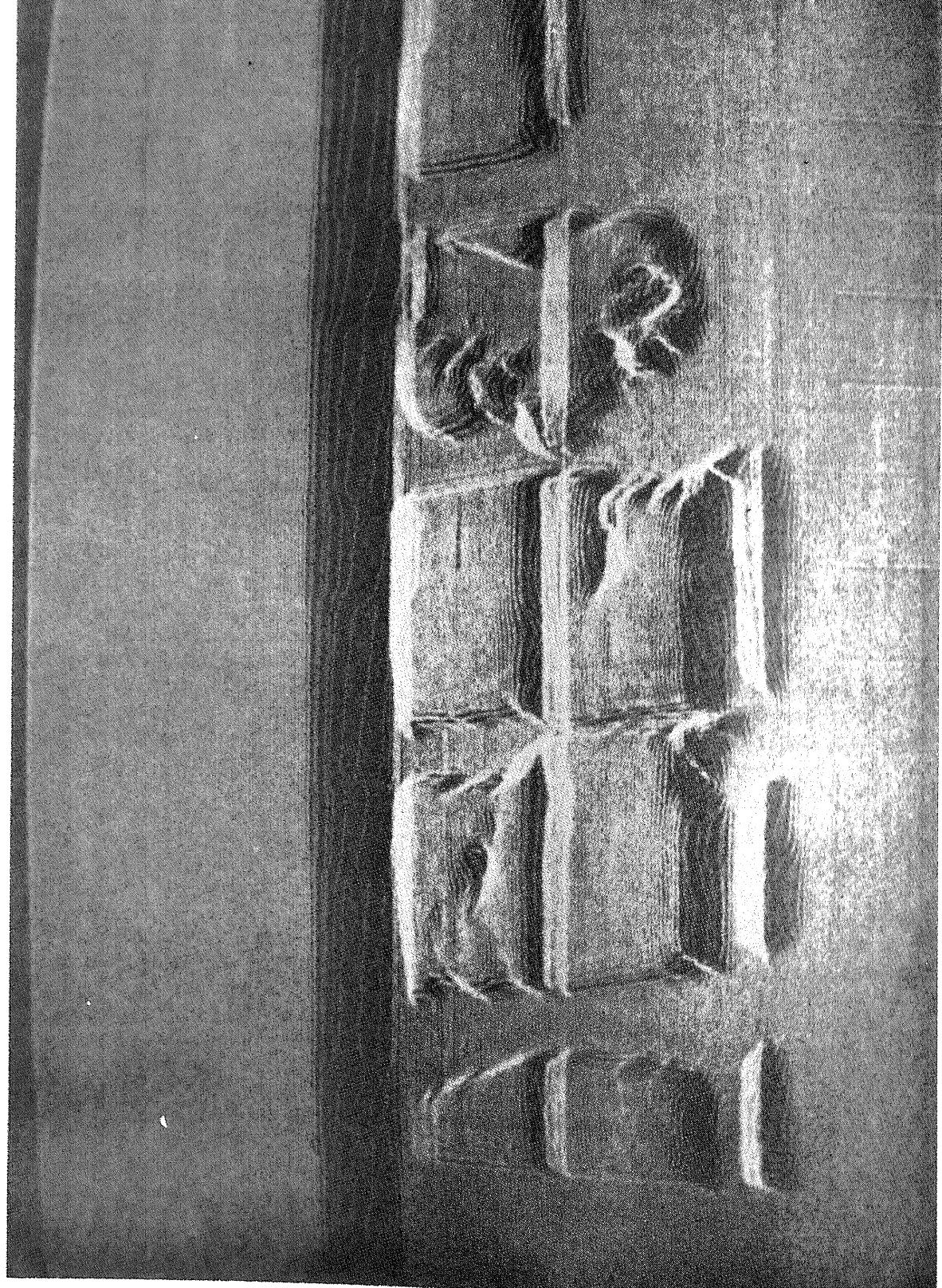


Figure 3 Isometric Rendition of SPIR Helicostat Image

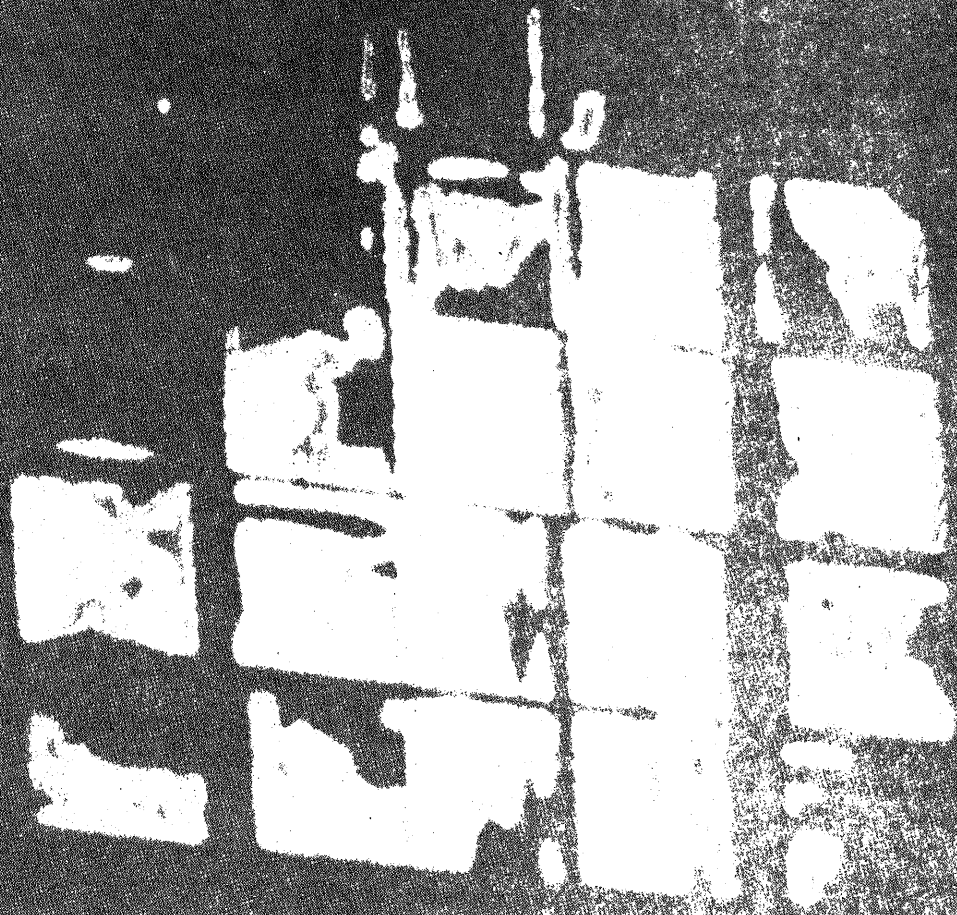


Figure 4. Color-enhanced Rendition of Solar Thermal Test Facility Heliostat near 100m East.

Freasier [2] for circular images and a 0.15 second response time), the author has suggested the following slightly more conservative expression for a safe exposure limit (E_{rs}). [1]

$$E_{rs} \text{ (w/cm}^2\text{)} = \frac{0.002}{d_r}$$

where the image diameter (d_r) is less than 0.002m and is expressed in meters. It is believed that under most circumstances there is probably an order of magnitude safety factor built into this criteria. [2]

Having determined the equivalent heliostat retinal image diameter, the safe irradiance limit can thus be specified. The irradiance level can then be compared to this safe limit, and a factor-of-safety can be determined.

While the technique proved to be very practical, the accuracy achieved was not very high because of the nature and the number of steps in the process. Short term variations in insolation or camera shutter speed, non-uniformities in film emulsion or the development process, optical distortions, electronic offsets and non-linearities, and intensity band integration all contribute to total error. A preliminary error assessment indicates that relative image area measurements are probably accurate to within ± 5 percent, but intensity measurements may be in error by 15 or 20 percent or even higher in certain instances. Since safety factors in the principal regions of interest (the airspace) were found to be comparatively large, however, this level of accuracy was considered adequate, and more extensive efforts aimed at reducing error contributions were not warranted for this series of investigations.

An example of the results obtained from the single beam measurements and evaluations is shown in Table I. The McDonnell Douglas heliostat with the improved mirrors and better alignment poses a potential safety hazard (safety factor less than one) as expected in the vicinity of its focal point (Table I), whereas it did not with the original facets. This is primarily attributed to better alignment during the second test rather than to higher reflectivity of the newer facets.

The Martin heliostat with a full complement of mirrors was measured as marginally unsafe around its best focal point which at the time of the test was somewhat short of its intended focal distance. It was still not optimally focused, however, so the safety factor could go somewhat lower.

Data on the Honeywell heliostat indicated that it was safe around its focal point, but one of the four facets was misaligned at the time the tests were conducted. Alignment of the fourth facet comparable to the other three would lower the safety factor to about 1.3 at its nominal focal point of 366m.

McDONNELL DOUGLAS HELIOSTAT (JULY 78)

DISTANCE (M)	RELATIVE IMAGE AREA	RELATIVE IMAGE POWER	EQUIVALENT RETINAL IMAGE DIA. (MM)	EQUIVALENT RETINAL IRRADIANCE (W/CM ²)	SAFE RETINAL IRRADIANCE (W/CM ²)
SUN	1.0	1.0	0.158	8.5	12.6
0	.89	.72	0.149	6.88	13.4
46	2.18	1.64	0.233	6.39	8.6
91	4.51	4.01	0.335	7.56	6.0
137	7.87	6.61	0.443	7.14	4.5
183+	6.44	4.64	0.401	6.12	5.0
366	.71	.47	0.133	5.63	15.0
488	.41	.31	0.102	6.27	19.6

+NOMINAL FOCAL POINT

TABLE I

course necessary in the zones where the focused beams are present. The measured values of relative retinal irradiance (the inverse of safety factor defined above) are shown for the STTF heliostat in Figure 5 compared to previously calculated values presented in Reference 1.

STTF HELICOPTER FLYOVER MEASUREMENTS

To experimentally assess eye hazards to personnel in overflying aircraft, several instrumented helicopter flights were made over the Solar Thermal Test Facility heliostat array in the summer and fall of 1977. There are 222 heliostats in the full heliostat field (Figure 6), but at the time of these initial flyover tests, only the first 78 heliostats were installed. The heliostat beams were all aimed at a standby point at an altitude of about 37m, just east of the tower. Their mean focal length was about 100m.

Four kinds of information were gathered. For quantitative retinal exposure data, a 16mm Action-Master 500 camera was used with an Agenieux zoom lens, an Inconel 3.0 filter, and Kodak Pan-X film. In an attempt to capture maximum heliostat image conditions, multiple photographs were made during each pass. Since the helicopter motion and the hand-held camera necessitated a larger field of view, the resulting images occupied only a small fraction of the negative frame area. In order to obtain reasonable resolution by the image processing system, photographic enlargement of the negatives was required. Because of the very small images and uncertainties about non-uniformities introduced by the additional enlargement step, no attempt was made to determine image irradiance. Only image area was measured. For the purpose of estimating a reasonable upper bound from a safety standpoint, a retinal irradiance of 6.8 W/cm^2 was assumed which corresponds to perfectly specular mirrors with about 80 percent reflectivity.

In an attempt to record the overall visual impression of the field as it would appear to a pilot of an overflying aircraft, the field was photographed in color with a 16mm Arriflex motion picture camera with a 12-200mm zoom lens during passes over the field at selected altitudes and from different directions.* An additional objective of these film strips was to try to assess, in at least a qualitative way, whether reflections from the field might be surprising enough to induce momentary flash blindness or otherwise be so distracting as to constitute a hazard even though levels were well below safe limits for retinal burns. Because the wide range of brightness proved difficult to accommodate, a canon Scoopic camera with a 12-100 zoom lens and automatic iris control was also used. Observers in the helicopter stated, when later viewing the films, that they provided a reasonably accurate overall impression, even though the brightness of the projected image was of course considerably lower. Observers also

*Portions of this film were included in the summary film shown at the symposium.

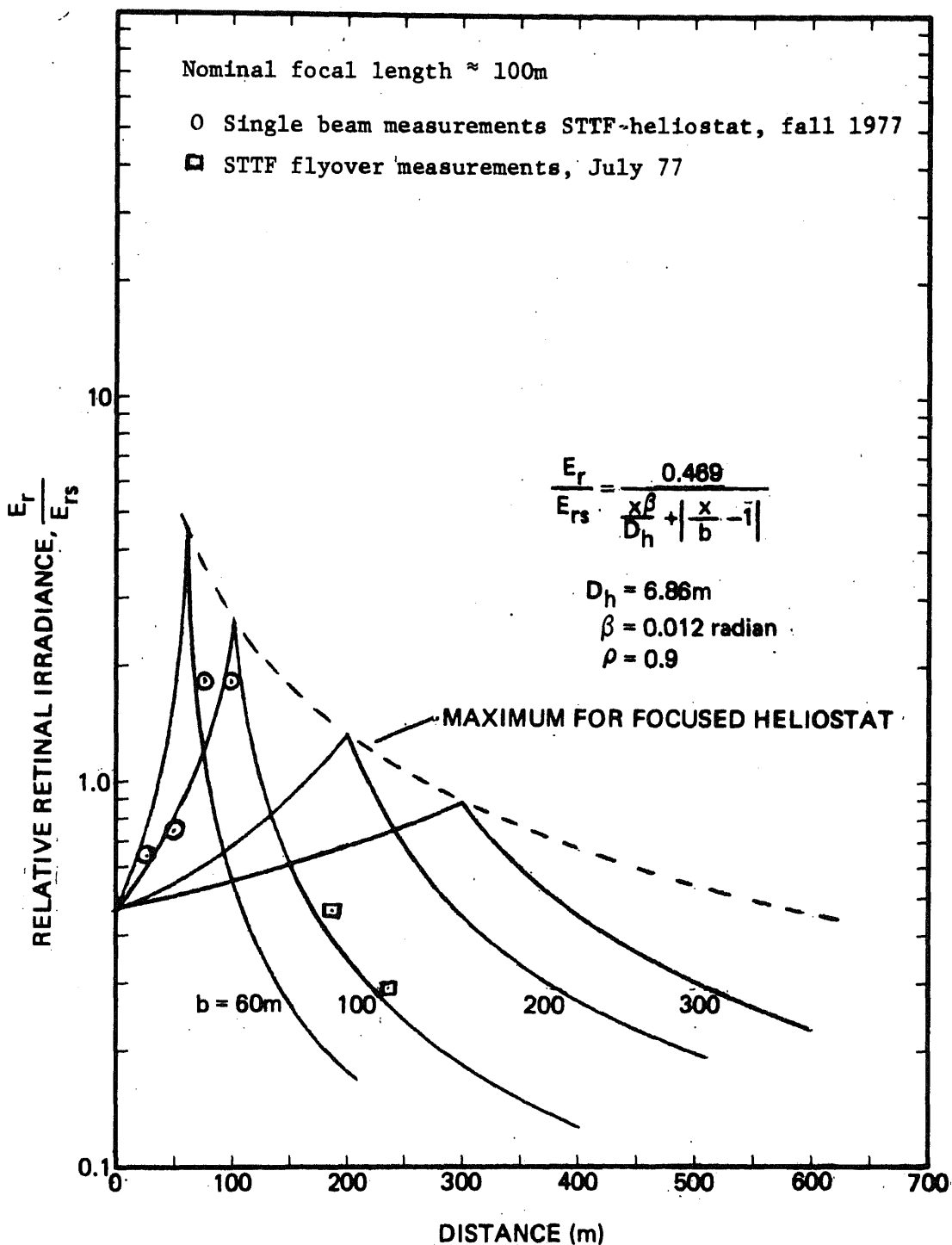
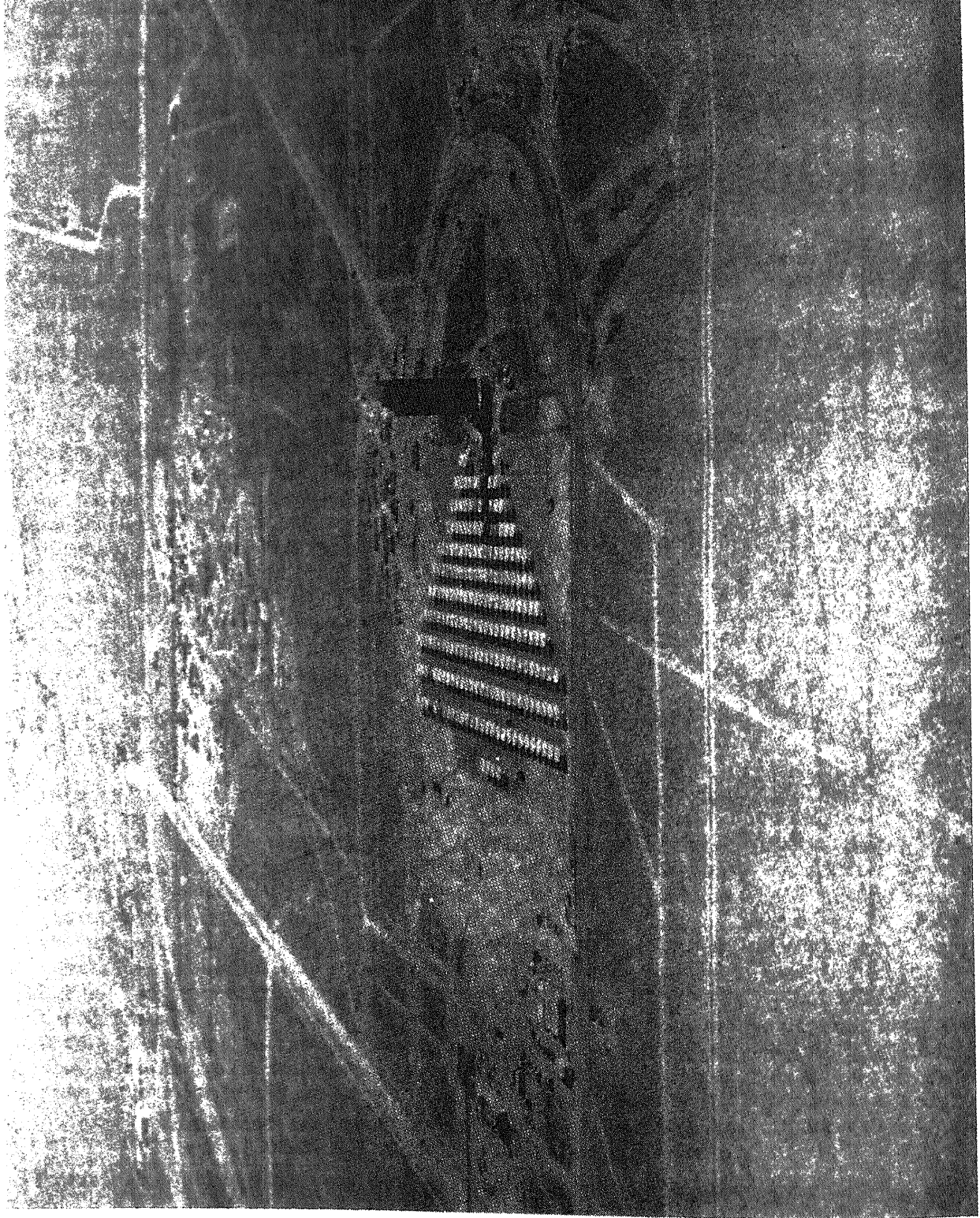


Figure 5. Comparison of measured relative retinal irradiance compared to values calculated in SAND76-8022, May 77

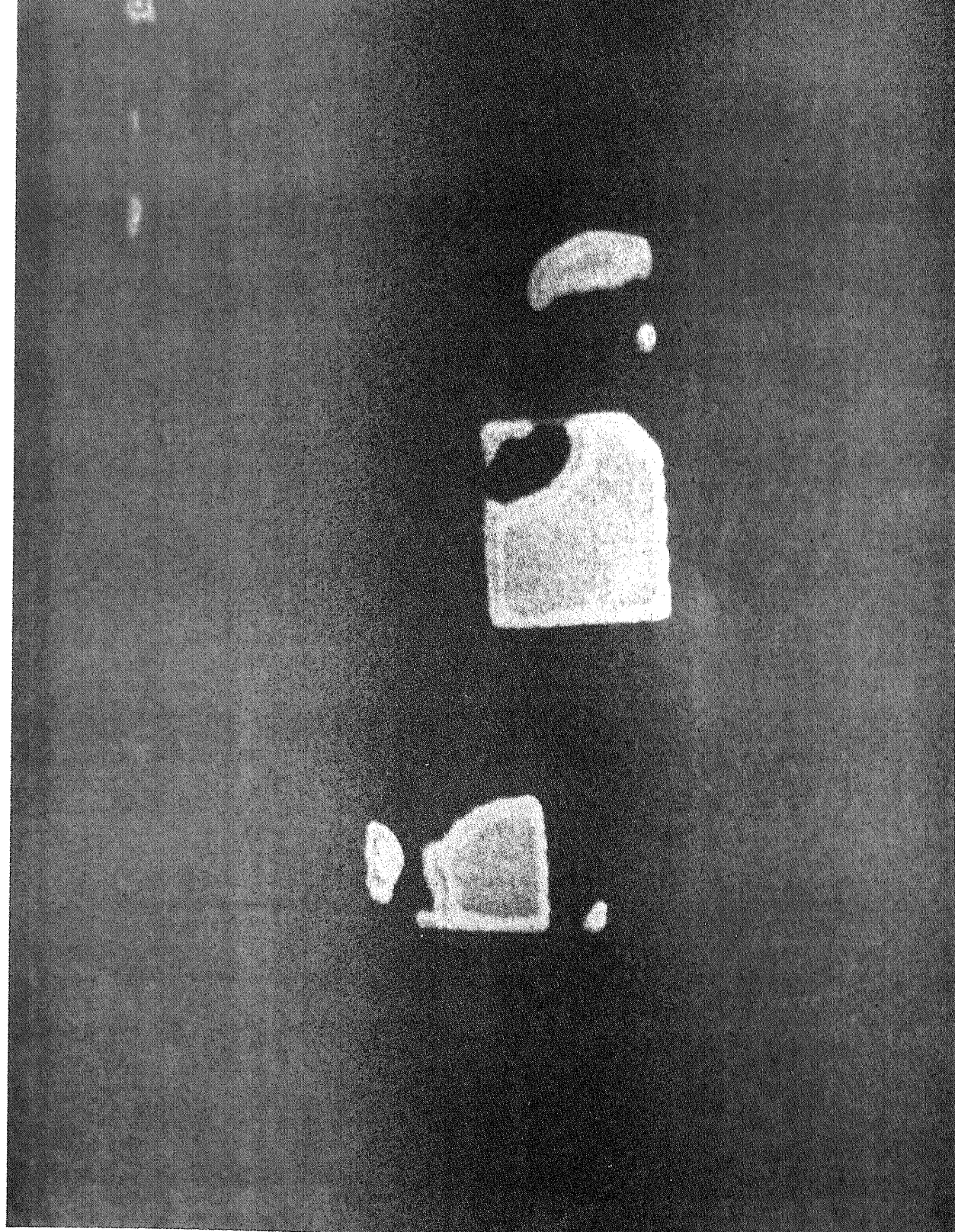


The fourth type of information was provided by observers in the helicopter. In addition to general first-hand impressions, two observations were of particular interest. The first was an assessment of the persistence of flash blindness. On several occasions, an observer (not the pilot) intentionally glanced directly at the field reflections, and then noted the time interval until he was able to read various indicators on the helicopter instrument panel. This interval was about 3-4 seconds. The second observation concerned the surprise element which is normally a prerequisite for flash blindness. Even though observers were obviously expecting reflections, it was noted that scattered light from dust particles and mirror imperfections was sufficient to provide considerable warning to the eye before entering a main beam. Given such warning, the natural aversion to very bright light and the blink reflex of the eye should tend to reduce the likelihood of temporary flash blindness. This effect could not be quantified, however, and it would be less advantageous for aircraft moving at higher speeds.

Measurements were made by flying the helicopter along preselected courses at 3 different altitudes, nominally 68, 87, and 124m. Motion picture and video cameras were operated continuously as the sun's image moved across the heliostat field in a direction opposite the flight direction. Multiple exposures with the Action Master camera were made when the reflections were near the center of the array. An example of the images obtained during the overflight at 68m altitude is shown in Figure 7. The maximum area of images measured at this altitude was about 80 percent of the corresponding sun image area. At 87 and 124m, the relative image area was about 30 percent and 2 percent, respectively. The results of the quantitative measurements are summarized in Table II. At the minimum altitude allowed by general FAA rules*, in the vicinity of structures such as the STTF tower, measurements indicated a large safety factor. At 124m (407 ft) above terrain the safety factor was about 13. Even at the minimum altitude flown by the helicopter, about 68m (223 ft) there was still a safety factor of about 2.

Shortly after these overflights, the video tapes were shown to FAA personnel at Kirtland Air Force Base at Albuquerque, and the results along with impressions of the observers and other findings were discussed. No major concerns were identified, and the general reactions were that the facility would pose no unusual hazard to aircraft personnel or interfere with normal aircraft operations in the area. However, special steps were taken to inform local helicopter pilots (who are not subject to the same FAA minimum altitude rules) about potential hazards of approaching the STTF too closely.

*152m (500 ft) above the structure. For the 60m STTF tower this would be 212m above terrain.



STTF HELIOSTATS

(FLYOVER MEASUREMENTS, JULY 77)

ST*	NOMINAL ALTITUDE (M)	RELATIVE** IMAGE AREA	EQUIVALENT RETINAL IMAGE DIA. (MM)	SAFE RETINAL IRRADIANCE (W/CM ²)	S	F
		1.0	0.150	12.6		
	68	0.81	0.14	14.3		
	87	0.31	0.088	22.7		
	124	.02	0.022	91	1	

NOMINAL FOCAL LENGTH = 100M
 MAXIMUM AREA OF 7 OR MORE PHOTOS AT EACH RANGE
 ASSUMING HELIOSTAT RETINAL IRRADIANCE AT 6.8 W/CM²

1. With the present beam control strategy at the Solar Thermal Test Facility measurements indicated no retinal burn hazard for aircraft personnel operating in accordance with general FAA rules.
2. The warning provided by scattered light reduces the likelihood of unexpected, momentary flash blindness of aircraft personnel; if encountered limited experiments indicated that impairment lasts for only 3 to 4 seconds.
3. Single beam measurements indicated that the two comparatively short focal length heliostats tested (STTF and McDonnell Douglas) pose a potential retinal burn hazard for momentary exposure in the vicinity of their focal points (100 and 183m, respectively, as tested). The longer focal length heliostats (Martin Marietta and Honeywell), if optimally aligned, could be marginally unsafe in the vicinity of their focal points (366m as tested). The unfocused Boeing heliostat is safe at any distance for momentary exposure.
4. Experimental measurements generally confirmed previous analytical evaluations of retinal eye hazards for single and multiple heliostat beams.
5. The special experimental techniques devised during these investigations show considerable promise for other heliostat evaluations.

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Thomas Springer

Rockwell International

Paper not submitted for publication in Proceedings.

INTRODUCTION

The Department of Energy/Sandia Laboratories Midtemperature Solar Systems Test Facility (MSSTF) in Albuquerque, New Mexico, has been in operation since late 1975. The MSSTF was constructed in support of the DOE's national Solar Thermal Power Program. Its objective is to develop technology for applying solar energy onsite to electrical power generation and other higher temperature applications such as industrial process heat. The MSSTF is, at 32 kWe, the largest solar electric power plant in the U.S. and also represents the world's first application of the solar total energy concept to an actual load, an 1100 m² office building.

DESCRIPTION OF MSSTF

The MSSTF (Figure 1) consists of two separate facilities, a Collector Module Test Facility (CMTF) and a System Test Facility (STF).

The CMTF (1) (Figure 2), is designed to obtain thermal and optical performance data for prototype collectors of up to about 45 m² in aperture. This facility presently incorporates three separately controlled fluid loops capable of testing three different collectors simultaneously. The three test stations use Therminol-66 heat-transfer oil to 315°C, high-pressure water to 330°C and 18.3 MPa, and low-pressure water to 110°C and 0.51 MPa. This latter loop is being modified to provide additional capability to test with heat transfer oils to 425°C.

The STF consists of solar collector fields, high- and low-temperature thermal storage facilities, an electrical power generation subsystem, a lithium-bromide absorption air conditioner, an instrumentation and control system, a weather station, and a cooling tower. The STF can produce 32 kWe and about 200 kWth. As an exercise in operating system feasibility, this energy can be supplied to a nearby 1100 m² office building. The component chosen for each segment of the STF was selected to be evaluated on a long-term basis for potential incorporation into larger solar power application projects.

*This work supported by the U.S. Department of Energy

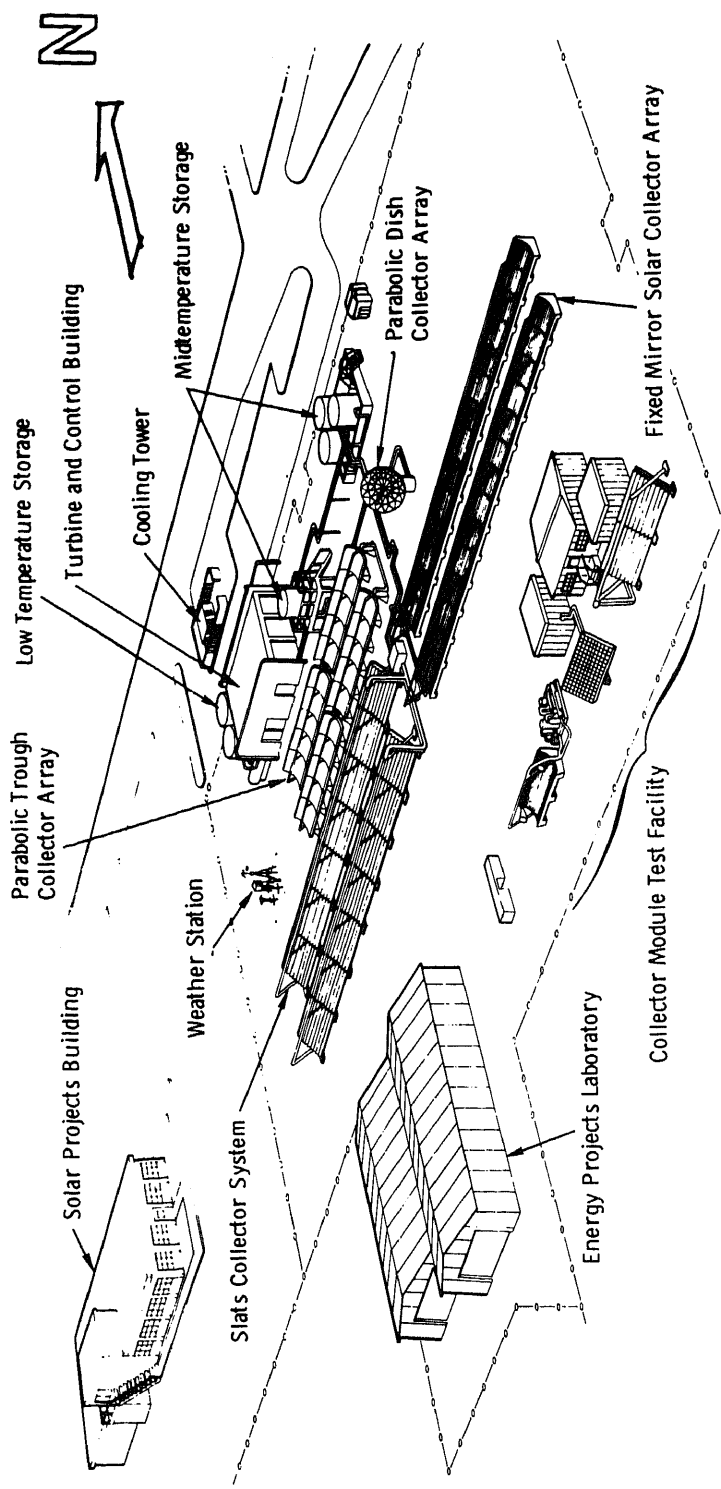


FIGURE 1 - Midtemperature Solar Systems Test Facility

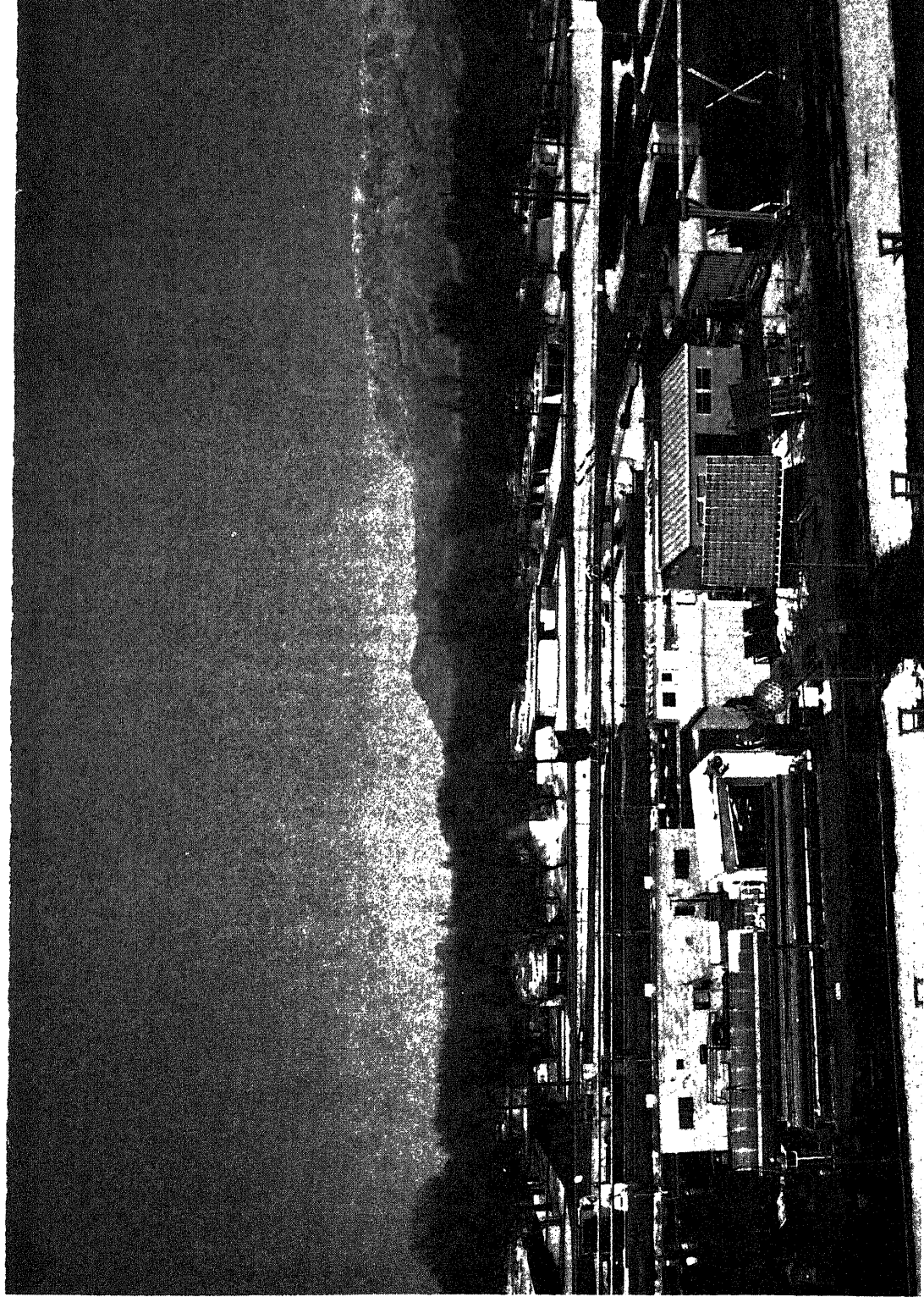


FIGURE 2 - Collector Module Test Facility

tubes at the focal line. A parabolic dish designed by Raytheon Inc., features two-axis computer controlled tracking. The fixed mirror solar collectors designed by General Atomic Co. are precision-cast concrete troughs, with silvered glass facets and feature a tracking receiver tube controlled by sun sensors. The SLATS collectors designed by Suntec Systems, Inc. feature mirrored slats that track the sun and focus radiation on a fixed-receiver assembly.

The high-temperature sensible-heat storage systems permit collection and storage of the heated fluid at acceptable working temperatures. The first, a single tank stratified storage system, is insulated by vacuum foil insulation. The second system consists of three valve connected tanks with bulk insulation. The heat transfer fluid and storage medium for both storage systems is a high boiling point oil (Therminol-66) which remains liquid with low vapor pressure at system working temperatures of 315°C.

A toluene heat exchanger is the interface between the heat transfer fluid and the turbine working fluid. Toluene is boiled and superheated by heat from the Therminol-66 and drives a single-stage turbine. The generator, with a peak electrical power rating of 32 kW, is shaft-coupled to the turbine through a gear train. Turbine condenser coolant water is drawn off and pumped to low-temperature storage tanks for subsequent use for operation of heating and cooling components.

ENVIRONMENTAL IMPLICATIONS

Many of the operations at the MSSTF have safety and environmental implications. Several examples are:

- Concentrating solar collectors
- Heat transfer oils at high temperature
- Water at high temperature and high pressure
- Superheated toluene as an organic Rankine cycle working fluid

200. Distributed solar collector modules typically have short focal lengths of less than 3 meters. This effectively eliminates any optical or thermal safety hazard to persons more than a few focal lengths away from the collector. A one-sun glint at longer distances may, in some cases, represent a nuisance or a vehicular hazard, but these problems can normally be dealt with by appropriate fencing and screening techniques. Workers and operating staff which must enter the optical hazard zone can be protected by goggles of the appropriate density, e.g., optical density 3 or greater for line focusing collectors. Casual observers must be prevented from entering the optical hazard zone by use of appropriate barriers and warning signs.

Heat Transfer Oils

Therminol-66 is the heat transfer oil used in the MSSTF. It is one of several commercially available products which are used in the 230-310°C temperature range. Others are Sun 21, Exxon HT-43 Caloria, and Dowtherm. All these materials are considered nontoxic, are relatively stable, and have low vapor pressure in the temperature range of interest. They are all flammable. Therminol-66 has a flash point of 194°C and an auto-ignition temperature of 374°C. Typical operating temperatures fall between these values which implies that a leak would not ignite upon exposure to air but would burn if exposed to an open flame. Indicated precautions are to minimize leaks at joints and fittings and to eliminate ignition sources in the vicinity.

Spills of heat transfer oil are prevented from entering the environment by use of retaining berms and automatic shut-off valve systems which actuate upon sensing unusual fluid storage level reductions.

High Pressure Water

It is technically feasible to use water as a heat transfer fluid at temperatures below the critical temperature of 373°C. High pressures are required to maintain very high temperature water in the liquid state. In the MSSTF, for operation at 330°C, pressures of about 18 MPa are impressed upon systems. These pressures combined with the corrosive nature of high-temperature water could result in the eventual rupture of pipelines or fittings which had good pressure integrity when installed. Although no such rupture has been observed at the MSSTF, caution will have to be exercised when installing high-temperature water systems commercially because the small solar

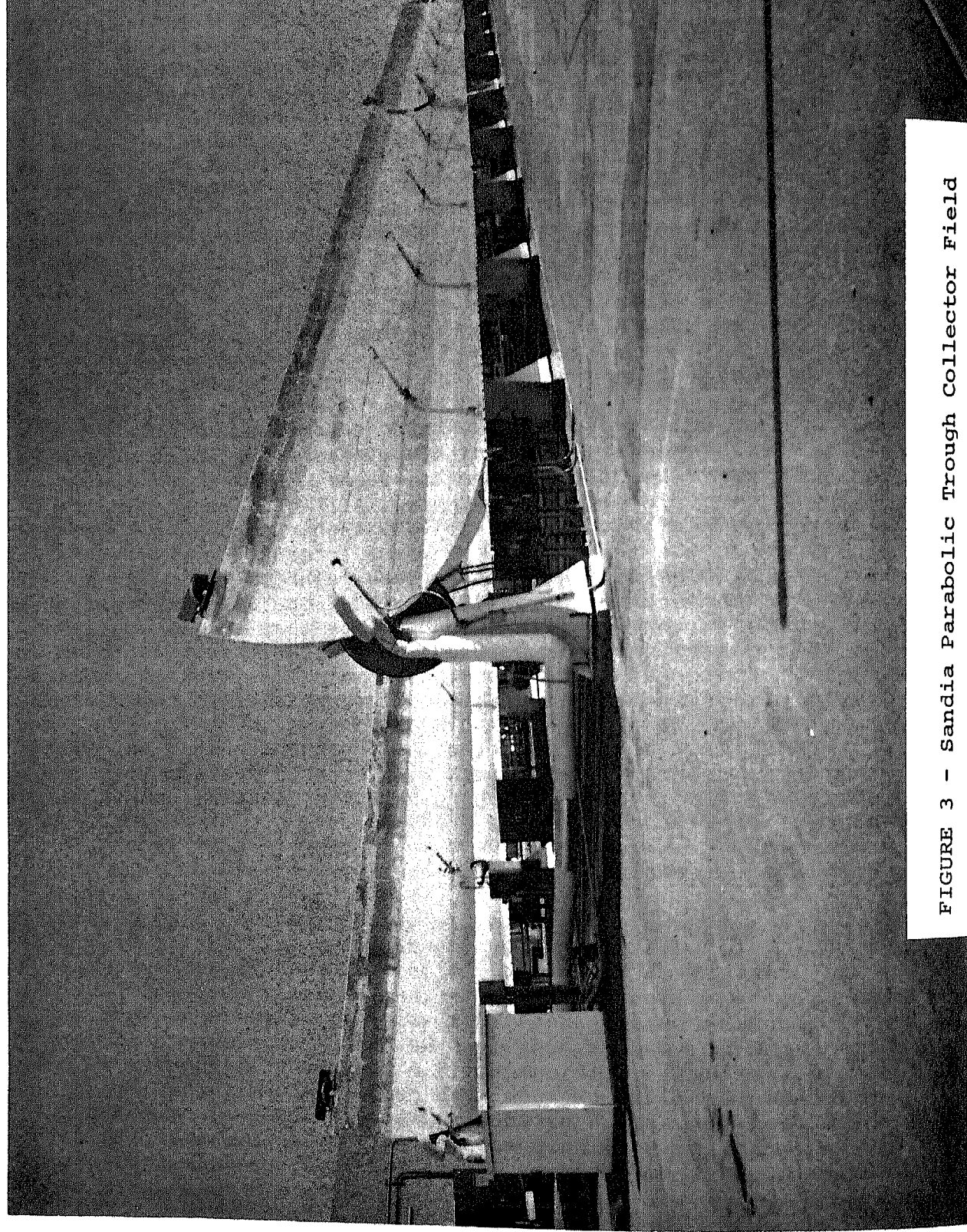


FIGURE 3 - Sandia Parabolic Trough Collector Field

Organic Rankine Cycles

Organic working fluids have several inherent advantages over steam for small power systems operating at moderate temperatures. This has made their use attractive to solar system designers. Toluene is the turbine/generator working fluid in the MSSTF (Figure 4). Because toluene is flammable, several precautions are taken. The toluene is employed in a closed loop. Smoking and open flame are prohibited in the turbine room which is also well ventilated during turbine operation. A carbon dioxide fire suppression system has been installed and can be automatically triggered by any of several over-temperature sensors. A toluene "sniffer" is also employed in the turbine room. This device will initiate a turbine shutdown when high vapor levels are sensed. Pressure relief valves backed up by burst discs protect the turbine/generator system from overpressure conditions. In the MSSTF, initial high pressure relief is vented into the condenser and retained, secondary venting if required is through a 2 m roof mounted stack to the atmosphere. For large commercial-sized systems the effects of substantial quantities of vented toluene will have to receive careful consideration.

Other solar power systems such as the Solar Irrigation Experiment at Willard, NM employ Freon working fluids. The use of Freon overcomes the flammability problems associated with most organics. On the other hand, environmental concerns have been expressed relative to the effect of Freon on the atmosphere. Hermetically sealed systems such as are used in refrigerators would help to overcome this and the toluene venting problems, but such systems would probably cost more than conventional heat engines.

CONCLUSIONS

The use of organic heat transfer fluids and heat engine working fluids are attractive for midtemperature, moderate-sized solar power systems because of certain performance advantages they offer. The use of organic fluids will require design solutions which are different from, and in some cases more difficult than, those of conventional power systems. On the other hand, such fluids are handled routinely in the petrochemical industry. The use of organic fluids can be made safe and environmentally acceptable if adequate awareness is established and if careful consideration to their unique properties is observed.

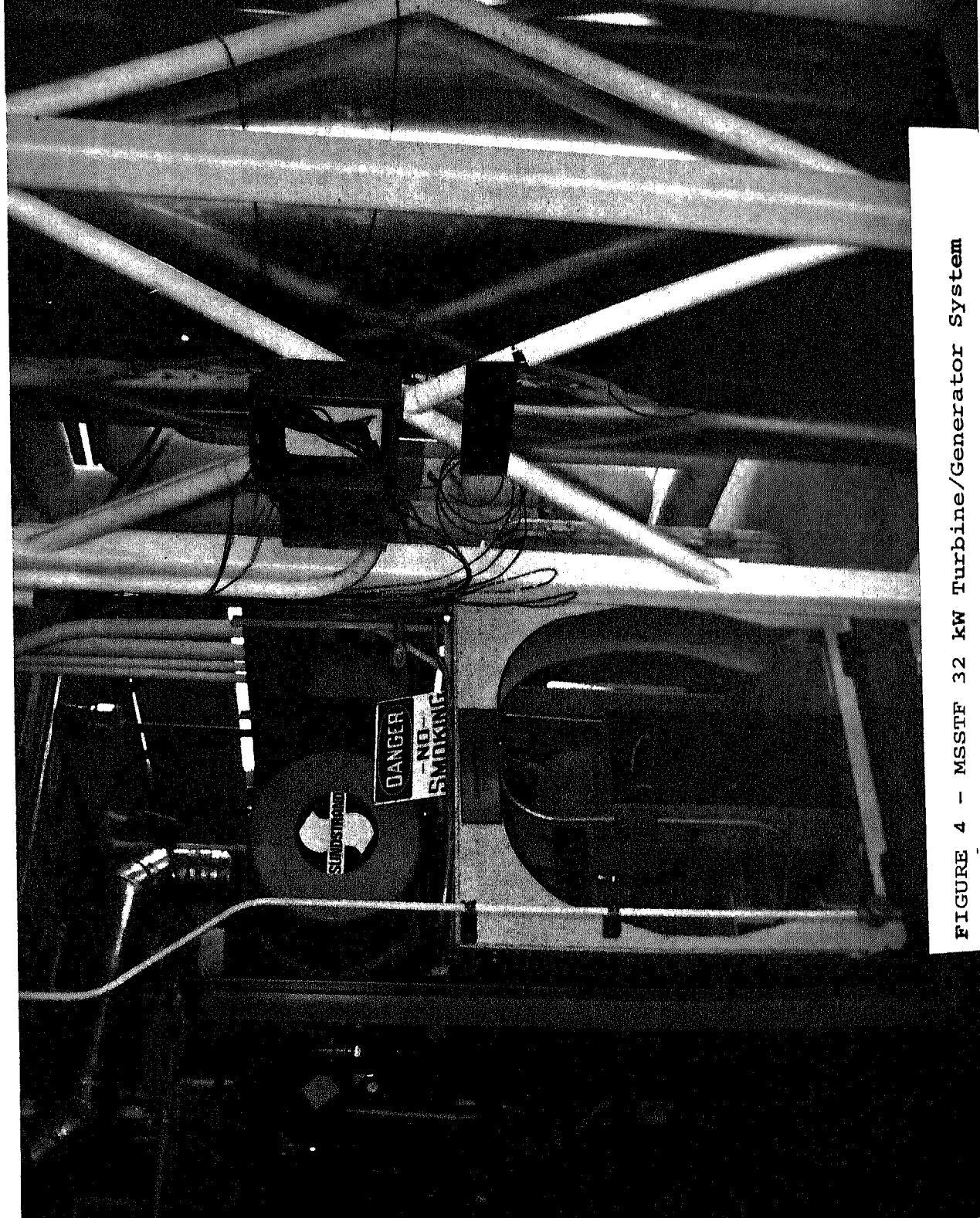


FIGURE 4 - MSSTF 32 kW Turbine/Generator System

Paper not submitted for publication in Proceedings.



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1. INTRODUCTION

The utilization of solar energy to heat and cool homes is often considered to be environmentally benign and to present few or no health hazards. However, all technologies impact the environment in which we live, and all technologies introduce situations that can lead to personal harm and property loss. Solar energy utilization is no exception.

The potential for environmental damage caused by any technology can be controlled in the most effective manner during the development stages of that technology. Past experience indicates that environmental or safety hazards associated with a well-entrenched technology are very expensive and difficult to correct. Furthermore, any well-publicized hazard or event can seriously retard public acceptance of a new technology. For these reasons it is essential to consider methods for minimizing environmental and safety hazards as an integral part of the development of any new technology. Solar energy utilization is still in an early enough stage that real hazards can be minimized if they can be identified, and if the information needed for hazard mitigation can be communicated to designers and users.

The technologies being developed for SHAC are extremely diverse, and the utilization of SHAC technologies will be at many locations. Environmental control devices for these varied, widespread technologies might be expensive to develop, and any added cost would retard public acceptance of SHAC systems.

The most effective overall strategy for mitigating health, safety, and environmental efforts caused by the utilization of SHAC technologies is an initial choice of materials and designs that avoids the hazards. The most effective tools for implementing this approach are informed users and designers. The challenge accepted by the project that this paper reviews is twofold: potential hazards resulting from the materials that could be used in SHAC technologies are to be identified; and, the hazardous properties of the materials are to be communicated to users and designers of SHAC systems. The vehicle chosen for conveying the information is a handbook of hazardous properties and environmental effects of those materials.

cluded. The reader interested in this data is referred to a recently published interim edition of the handbook.*

2. THE CONCEPTS OF A HAZARDOUS MATERIAL PROPERTY AND A HAZARD

A hazardous property of a material is not a hazard; instead, it is any material property that can lead to personal harm if the material is used improperly. A hazard exists when a material or object is used in a manner that does not adequately protect against its dangerous property. Any realistic assessment of the degree of a hazard must consider both the properties of the material and the likelihood of exposure. Materials with very hazardous properties can be used in a safe manner if the hazardous properties are recognized and controlled.

In this short paper some potential hazards are identified for categories of materials. This does not mean that the use of all possible materials in an identified category leads to undesirable consequences. Indeed, the reason for the identification is to guide choices of materials from that category that do not lead to a hazardous situation.

3. SAFETY RISKS

Safety risks are those potential hazards that can lead to illness or injury. The chief safety risks associated with SHAC materials result because of the toxicity and fire properties of the materials. Some potential hazards are not substantially different than those already present in a home, but some are new and unfamiliar to the average home owner. Most safety risks that are unique to SHAC systems result because of the incorporation of materials not usually used in the building industry, or because of a new use of familiar materials.

Active SHAC systems present more potential hazards than do passive systems for several reasons. Since active systems operate at high temperatures, thermal degradation of materials is more likely. Degradation products may be more toxic and fire hazardous than the original material. Seriously degraded materials must be

*Jimmie Q. Searcy, Editor "Hazardous Properties and Environmental Effects of Materials Used in Solar Heating and Cooling (SHAC) Technologies: Interim Handbook" SAND 78-0842, August 1978. (Available from National Technical Information Service; U. S. Department of Commerce; 5285 Port Royal Road; Springfield, VA; 22161 - Price: Printed Copy \$9.50, Microfiche \$3.00).

Active systems use a much wider variety of materials than do passive ones, and some of the potential materials (heat transfer fluids, heat storage media, and collector coatings) are not normally found in a home. Most passive systems use materials that are relatively innocuous and already in common use in buildings.

There are several types of potential exposure that make the toxicity of materials very important. The most obvious example is associated with the use of liquid heat transfer fluids in systems generating domestic hot water. Any leak through the heat exchanger would contaminate the water and increase the possibility of accidental ingestion of the heat transfer fluid by occupants of the dwelling. Another potential exposure results because organic materials (plastics, sealants, insulations, insulation binders, wood) give off gases at elevated temperatures. These gases may be transported into living areas. Dusts and fibers released by insulations can also be carried into living areas in systems that use air as the heat transport medium. In addition, there are the ever present problems of accidental ingestion by children of any fluid or solid available to them, and the routine exposure of installers of SHAC systems to vapors and dusts from the materials.

The degree of toxicity hazard caused by an exposure is determined by the duration of the exposure, the concentration of the toxic material, and the toxicity of the material. Some materials may appear relatively innocuous because a single massive exposure does not cause immediate, observable effects. However, that same exposure may cause effects at a later time, or repeated exposure to low levels of that material may cause toxic effects. The most feared effect that appears after a time delay is cancer, but others are possible.

Fire safety of SHAC systems depends to a large extent on the spatial arrangement of the system in a home, and the fire properties of the materials. A wide range of flammability exists for the various materials that may be used in SHAC systems.

There are several unique situations related to fire safety that may be introduced to private homes by certain SHAC systems. Some potential liquid heat transfer fluids are flammable. Heat transfer liquids are used at elevated temperatures, and any leak of a hot flammable liquid near an ignition source could lead to a fire. Wood degrades slowly when maintained at elevated temperatures, and its autoignition temperature decreases significantly with this degradation. This can lead to a fire hazard. For this reason, most manufacturers do not use wood as a structural material in collectors. However, private individuals favor wood because of its ease of fabrication and installation.

(mining and manufacturing, etc.) environmental concerns resulting from the activities that are necessary to provide the materials are not considered here. Impact on the environment caused by the normal operation of SHAC systems appears to be minimal and localized. In a few abnormal situations (such as fires and fluid spills) there is a possibility for environmental damage on a small scale.

Those environmental concerns that are considered by this project result from the improper disposal of the materials. No significant environmental effects can be attributed to SHAC technologies at the present time because current utilization is so limited. As the use of SHAC technologies increase, environmental effects could become significant if improper disposal practices are prevalent.

Most of the structural and insulating materials used in SHAC technologies are the same as those already in wide use. The increased use caused by SHAC technologies will be small when compared with the quantities already being used, and environmental effects caused by the disposal of the additional amount is not expected to add significantly to the environmental impact already caused by the disposal of these materials.

SHAC materials that are not currently in wide use in the building industry are generally those used as heat transfer fluids, collector coatings, and heat storage media. Disposal of large amounts of these materials could present significant new problems, especially if certain of the more hazardous materials are widely used. The potential problems are complicated by the fact that disposal of these materials will be done by the individual homeowner in relatively small amounts over a large area, and in an unpredictable manner. There are at present no comprehensive regulations that control indiscriminate disposal of materials by individuals, and it is unlikely that one could be enforced if it existed.

The materials that are most often suggested as environmentally hazardous are the liquid heat transfer fluids and their additives. The fluids are glycols, silicone oils, and hydrocarbon oils. They are not particularly hazardous materials, but some of the additives that may possibly be used in them are. Some of the chemicals that are potential additives persist in the environment for long time periods, some may bioaccumulate and enter food chains, and some may be carcinogenic. In addition, there is the possibility that heat transfer fluids disposed of through the sanitary sewer system can react with chlorine to form materials that are much more hazardous and persistent in the environment. Whether or not the disposal of heat transfer fluids becomes a problem at some future

5. HANDBOOK DEVELOPMENT

The handbook being developed by this project represents an attempt to collect the pertinent hazardous materials information relative to health, safety, and environmental effects, and to present this information in a lucid manner to designers and users of SHAC technologies. Large amounts of data must be systemized in some manner that makes specific information easy to find. In the handbook materials are categorized according to functional use. Those categories are heat transfer fluids, insulations, sealants, glazings, collector materials, and storage media. A discussion of each category and data tables for materials in that category are included in each of the informational chapters.

Each informational chapter discusses a single topic. These topics are chemical composition and thermal degradation products, toxicity properties, fire hazard properties, and environmental effects.

Comments and participation in the development of the handbook are solicited from any qualified spokesperson. Since the development of SHAC technologies is so dynamic and varied, no small group of investigators could hope to present a complete tabulation of SHAC materials or potentially hazardous situations. Therefore, collaboration with individuals and groups active in the utilization of SHAC technologies is a very important part of the handbook development. Cooperation with standards and code writing groups and the structuring of the document in a manner that complements their activities are also major goals of the project.

An interim version of the handbook has been published and is available for public sale through the National Technical Information Service.* This interim handbook will be updated twice during the next fifteen months to include additional data and discussions. Specific data generated by other DOE projects relevant to the goals of the handbook will be incorporated. Meaningful contributions, suggestions, and data from any other source will also be included.

*See earlier reference. (A limited number of copies are available from the author of this paper.)



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Chairman: Andrew Krantz
Co-Chairman: Robert Blaunstein

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ASSESSMENT AND CONTROL OF OTEC PHYSICAL ENVIRONMENTAL IMPACTS

J. D. Ditmars

Argonne National Laboratory

The operation of an Ocean Thermal Energy Conversion (OTEC) plant requires the intake and discharge of large amounts of ocean water. A 100 MW OTEC plant may require the intake of about 500 m³/s of warm surface water for the evaporators and of about an equal flow of water colder by some 20C° from as deep as 1000 m for the condensers. The discharge of these flows, changed in temperature by a few Celsius degrees, back into the environment will result in perturbations to the natural distributions of temperature, salinity, nutrients, and other water constituents. Also, the possibility exists that leaks of working fluids and the products of corrosion within the plant may be transported to the environment in the plant effluents.

Assessment and control of the impact of OTEC to the chemical and biological ocean environment requires knowledge of the modifications to the physical environment due to the transport and mixing of the plant effluents. Modifications to the ocean temperature structure also impact the plant operation, and control of environmental impacts must be reconciled with maintenance of the thermal resource.

Studies regarding the physical impacts of OTEC consider several scales of perturbations to the ocean environment. Near-plant perturbations are dependent on the vertical locations of intakes and discharges and on whether evaporator and condensor discharges are separate or mixed. Ambient currents and stratification affect the transport of effluents initially and may dominate large-scale ocean perturbations. Questions regarding the deployment of many OTEC plants, in the Gulf of Mexico for example, require the examination of large-scale processes. The results of mathematical and physical model studies are being employed to assess impacts and means of control for both single and multiple-plant deployments.

ASSESSMENT AND CONTROL OF OTEC ECOLOGICAL IMPACTS

P. Wilde et al.

Lawrence Berkeley Laboratory

Design for siting modifications may be necessary to insure ecologically sound operations of Ocean Thermal Energy Conversion (OTEC) plants. Currently, site survey and laboratory studies are being conducted in regions of interest for OTEC. Data will be used to estimate environmental impacts of OTEC plant operations and serve as baseline data for operational monitoring. Mitigating

discharge at depth. Maximum tolerance (LD50) for chlorine) can be estimated using results of toxicity studies now under way. Impingement and entrainment effects can be reduced by use of screening or fish warning devices.

AN OVERVIEW OF WIND ENERGY CONVERSION SYSTEMS ENVIRONMENTAL ISSUES

Arthur C. Parthe, Jr.
The Charles Stark Draper Laboratory, Inc.

WECS are one of several alternative means of generating electrical energy that are currently being developed under DOE project management and funding. If WECS prove to be technically and economically "successful," the ultimate potential will only be realized by installing several hundred thousand units across the U.S. These installations will be, of necessity, primarily concentrated in the higher wind regions that have accessibility to electric power distribution networks.

Environmental impacts of concern could arise from two primary situations. The first is from in situ situations that are adversely affected by the presence and/or operation of a WECS. The second is from effects that are created and/or aggravated by the proximity of WECS to residential and commercial areas, the impact of which is judged undesirable.

The potential negative consequences of both situations may be of an intermittent, condition-specific, or continuous nature. Those of the latter can only be controlled by not installing the WECS. However, intermittent and condition-specific problems/effects can be controlled by restricting and controlling levels and/or times of WECS operation, so as to minimize environmental problems.

WECS have potential problems in all three above mentioned situations. These problems have been recognized by DOE and are being assessed, studied, and/or evaluated with respect to consequences and solutions.

ELECTROMAGNETIC INTERFERENCE CAUSED BY HORIZONTAL AXIS WIND TURBINE GENERATORS

D. L. Sengupta and T. B. A. Senior
University of Michigan

Since 1976 The Radiation Laboratory, under sponsorship from DOE, has been studying the effects of large horizontal axis wind turbine generators (WTG) or windmills on the performance of various electro-magnetic systems, and the present paper summarizes our investigation to-date.

This extraneous modulation of the desired signals, if sufficiently strong, can adversely affect the performance of an electromagnetic system. The degree and nature of the interference will depend on the signal transmission and reception methods used by the system, and the electromagnetic scattering characteristics of the WTG blades.

We have carried out a wide-ranging theoretical and experimental investigation of the electromagnetic effects of large horizontal axis WTGs on the performance of TV and FM broadcast reception, microwave communication link and air navigation systems. In the following paper we summarize the work done in the different areas and highlight the significant findings.

ENVIRONMENTAL ASPECTS OF WOOD ENERGY CONVERSION

C. J. High and Charles E. Hewett
Dartmouth College

The environmental aspects of the technologies under the jurisdiction of the Fuels from Biomass Programs will be presented. Positive as well as negative impacts will be discussed. Some treatment will be given to the specific topics of particulate and toxic substance control.

ENVIRONMENTAL AND SAFETY CONSIDERATIONS FOR SOLAR HEATING AND COOLING APPLICATIONS

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The HUD Minimum Property Standards (MPS) and the "residential" and commercial" interim performance criteria (IPC) prepared by the National Bureau of Standards address many health and safety considerations that need to be considered by solar heating and cooling system designers. For example, factors such as the toxicity and flammability of heat transfer fluids are often not considered in the design of systems. Similarly, attention is seldom paid to the safe disposal of these fluids. These problems are compounded by the lack of clear guidelines as to which fluids constitute hazards that warrant special consideration. This report is intended to create an increased sense of awareness of the health and safety aspects of solar heating and cooling applications by extracting and amalgamating pertinent provisions of the MPS and IPC documents. Some of the areas that are addressed include: structural safety, heat transfer fluid toxicity and flammability considerations including the protection of potable water, effects of solar equipment on the fire resistance of buildings, and protection from physical hazards.

INTRODUCTION

The purpose of this paper is to summarize the status of studies directed toward the assessment and control of physical environmental impacts associated with OTEC plant operation.

Ocean Thermal Energy Conversion (OTEC) is a solar energy technology in which power is generated by utilizing the temperature difference between the warm, surface water and the cold water at depth in the subtropical and tropical oceans. The temperature difference is used to drive a heat engine in which the warm, surface water is used to expand a working fluid (probably ammonia) which drives a turbine and the colder water at depth is used to condense the ammonia back to the liquid state. The temperature difference across the evaporator and condenser of the power plant is often called the *thermal resource* and is expected to be about 18-22°C. Consistently available thermal resource of this magnitude, in the subtropical and tropical oceans, requires that cold water be drawn from depths as great as 1000 m. Exploitation of this energy resource could be accomplished in one of two modes: by means of either fixed or moored plants in the vicinity of a coastline to which electricity could be transmitted, or by means of plant ships which would graze the ocean areas containing the resource and produce energy-intensive products such as aluminum, hydrogen, or fertilizers. Potential site regions for moored OTEC plants are the Gulf of Mexico and the waters off Hawaii, Puerto Rico, and Guam. Grazing plants might operate in a number of locations, although presently attention is focused on the South Atlantic Ocean.

With a thermal resource of 20 C°, the overall thermal efficiency of a OTEC plant is expected to be about 2.4%. At this low efficiency, a 100 MW (net) OTEC plant would require evaporator and condenser seawater flow rates $\approx 450 \text{ m}^3/\text{s}$ each, or a total plant intake of about $900 \text{ m}^3/\text{s}$ of seawater. The condenser flow rates alone are about 10 times the typical cooling water flow rate required by a 1000 MW nuclear generating station. Surface water taken into the evaporators would be discharged into the environment about 2 C° cooler than at intake, and cold water passing through the condensers would be returned to the environment about 2 C° warmer than it entered. While a relatively clean source of power, OTEC plants are not expected to operate without some impact on the environment. The possible environmental impacts of OTEC deployment in the oceans have been enumerated elsewhere, particularly in the Environmental Development Plan (EDP)¹, and the assessment of ecological aspects of OTEC are discussed elsewhere in these proceedings.² Central to the ecological assessment of OTEC impacts is an understanding of physical impacts to the ocean environment due to OTEC.

environment. Perturbations to the natural distributions of temperature, salinity, nutrients, and other water constituents are of concern. The fate of substances added to the ocean by OTEC plant operation, such as biocides and corrosion products from heat exchangers, depends on the transport and mixing of the large plant effluents in the ocean environment. Likewise, the fate of leaks of working fluids, such as ammonia, must be assessed. Determination of the spacing of individual OTEC plants in power parks or of the spacing between power parks in a large water body raises questions about plant-plant interactions and "downstream" or wake perturbations. The ultimate energy yield of a particular area clearly depends upon the spacing allowed for individual OTEC plants. Decisions regarding the deployment of several 100 MW plants vs fewer 400 MW plants are, in part, related to plant spacing limitations. OTEC plant operation may result in lowering of sea surface water temperatures. It is known that microclimates are sensitive to rather modest changes in sea surface temperature, and the effect of OTEC plants on the atmosphere and, thus climate, requires assessment. Another climatic effect which has been raised regarding OTEC is the contributions of OTEC plant operations to atmospheric CO₂ balances. Assessment of the physical environmental impacts of OTEC includes a variety of physical scales, ranging from relatively small-scale, near-plant processes to scales of motion as large as the circulation in the Gulf of Mexico. This paper seeks to describe the research results presently available in those ongoing studies which address physical impacts of OTEC for this multitude of scales.

NEAR-PLANT ENVIRONMENT

An OTEC power systems concern, with environmental ramifications, is the degradation of thermal resource or recirculation. Thermal resource degradation can occur due to either direct recirculation of evaporator and condenser effluents to the evaporator intake or indirectly by modification of near-surface water temperatures due to flows from the plant. For typical proposed closed cycle OTEC designs, any fractional loss in the available thermal resource is amplified by a factor of about 2.4 in terms of the corresponding fractional loss net power output. For example, for typical operating conditions the fractional loss in net power output for a 1 C° loss in thermal resource is about 10%. While plants will be designed to accept some variability of thermal resource, significant thermal resource degradation could jeopardize significantly plant efficiency. Consequently, efforts have been underway to design discharge systems for evaporator and condenser effluents such that resource degradation or recirculation are reduced to acceptable levels. It is important that designs with the intent of minimizing the degradation of thermal resource do not lead to unacceptable environmental impacts. Plant design -- in particular size and location of the intake and discharge ports -- clearly determines the extent of the recirculation a plant will experience at a particular site under specific ocean conditions. Various intake and discharge concepts have been proposed. These include horizontal and vertical warm-water intakes, axisymmetric and directional intakes, horizontal and inclined discharges, mixed and separate

vantage of natural ocean currents to minimize recirculation effects. Inclined and mixed discharges have been proposed to take advantage of negative buoyancy and natural ocean stratification to minimize recirculation effects. In order to choose an intake and/or discharge design that is likely to result in minimal loss of thermal resource, the various concepts must be evaluated under several ocean conditions that are expected to be critical to OTEC operation. Such conditions clearly should include ambient currents and mixed layer depths comparable to those normally expected at proposed OTEC sites.

The flow field produced near an OTEC plant by the interaction of the plant intake and discharge flows with local ambient currents and density stratification is complex. Detailed analytical and numerical simulations for this type of flow field are unlikely to be successful in the near future. Consequently, physical (hydraulic) laboratory scale model studies have been undertaken to investigate the behavior of jets near the plant and the problem of recirculation.

Physical model studies at Hydronautics, Inc.^{3,4} were directed primarily toward the case of separate discharges, that is, effluents from the evaporator and from the condenser were discharged separately into the environment. For separate discharges, the condenser water discharge is negatively buoyant with respect to the receiving water in the upper part of the ocean and is expected to sink to depth. However, evaporator discharge (surface water reduced in temperature by only 2 C°) may be only slightly negatively buoyant with respect to the environment, depending on the temperature structure in the mixed layer. The opportunity for direct recirculation of the evaporator effluent to the evaporator intakes exists. Model studies for schematic intake and discharge structures indicate that the primary parameters governing recirculation were the separation distance between the intake and evaporator discharge and the strength and orientation of the ambient current. Direct recirculation to the intake seems to be rather small for cases in which the separation distance between intake and discharge is greater than about two discharge diameters. Note, however, that typical discharge diameters may be about 20 m, and, consequently, separation distances as large as 40 m may be required. For reference, typical mixed-layer depths are on the order of 80-140 m. The Hydronautics studies also indicate that the behavior of the plant effluents and the degree of recirculation depend on the angle of the discharge relative to the ambient current. For discharges in the same direction as the ambient current (co-flowing) or perpendicular to it (cross-flowing), recirculation seems to be small. For the case of discharge head-on into a current, recirculation seems to be maximum, but that larger recirculation is realized for only a rather narrow window of velocity and discharge parameters. The model studies suggest that, for typical OTEC designs in which intake and discharge ports are spaced rather closely and symmetrically distributed about the plant, the recirculation will be about 10-15% corresponding to a loss in net power of about 2-3%. Variations in discharge buoyancy, density stratification, and the effect of flow around the plant structure itself may act to increase the degree of resource degradation above these values.

results in a combined effluent which is much colder (denser) than the typical waters found in the mixed-layer region. Consequently, one would expect that this mixed discharge would sink to the bottom of the mixed-layer region and spread out in the region of the thermocline or below it. The results of the MIT studies confirmed this expectation, and the experiments showed no measurable change in the warm water intake temperature due to the presence of the mixed discharge for reasonable discharge flow rates and temperatures for schematic plants up to 200 MW. Maximum currents in these studies, however, were only about 0.1 m/s (prototype), and experiments at higher ambient currents are underway at present. A criterion for recirculation under simplified two-layer ocean conditions was developed on the basis of these laboratory experiments and indicated that plants using mixed discharges up to sizes of 400 MW could operate without significant recirculation. Additional experiments conducted recently at MIT for continuous stratification have tended to confirm this result.⁶

Another near-plant issue which has received some attention is that of the intakes of surface water. In addition to the obvious problems of screening and fouling by biological organisms⁷, there remains the question of the design of the intakes to allow sufficient inflow of warm, surface water without withdrawing deeper, colder water and degrading the thermal resource. Physical model studies have indicated that it is unlikely that, for the rates of flow envisioned and for normal mixed-layer depths, cold water would be drawn up into the intakes.

From the point of view of recirculation and degradation of thermal resource, it appears that mixed discharges reduce the probability of resource degradation. However, if recirculation of mixed discharges does occur, the consequences in terms of power penalties are greater. It appears, at this time, that the recirculation aspects of the near-plant environment can be solved by appropriate engineering design of the separation of intakes and discharges and the orientation of effluent jets. However, from an environmental point of view, the question may not be answered so simply. Mixed discharges, while providing protection against recirculation, may promote adverse environmental conditions. Preliminary model results indicate that mixed discharges will probably sink to depths in and around thermocline. These depths may represent the lower edges of the photic zone, and the introduction of nutrient rich cold water at this level may result in increases in primary productivity. Bathen⁸ provided preliminary estimates of the increases in biostimulation that result from OTEC effluent disposal from a power plant off Keahole Point in Hawaii. Also, depending on natural temperature and salinity stratification and plant design, OTEC-created water masses may be anomalies in terms of temperature and salinity. Thus, the development of appropriate strategies for the discharge of OTEC plant effluents requires knowledge of the physical transport and mixing mechanisms and of the ecological effects of mixing surface and deep waters and of placing them at some intermediate depth. Ongoing chemical and biological characterizations of potential site waters should provide data for such assessments.

plant. Beyond this region, the behavior of the effluent plumes from the OTEC plant are not directly dependent on the discharge and intake configuration. The velocity of the plume has been decreased such that the plume is likely to move at about ambient ocean current speeds. Vertical and lateral spreading of the plume dominate relative plume motion. Movement of the plume is governed primarily by gravity spreading, due to small density differences between the effluent and its surroundings, turbulent diffusion processes, and possibly salt fingering. The additional mixing of the plant effluents in this region, known as the *intermediate-field*, is expected to be less than that found in the near-plant environment. These plumes, in the wake of OTEC plants, may maintain their individual integrity for distances of tens of kilometers. Interest in the intermediate-field mixing is prompted, not only by the need to know the fate of pollutants at such locations downstream, but also by the desire to establish a spacing criterion for individual plants within a power park.

Preliminary analyses by Jirka⁹ have indicated that ambient current and plant discharge rates (size of plant) are important parameters in determining the vertical and lateral extent of plumes in the intermediate field. He has shown that the vertical growth of plumes can weaken density differences which act to inhibit recirculation. If such weakening occurs, then recirculation at plants downstream from the initial source plant might occur. Consideration of such plume dynamics leads to some initial indications of spacing for plants in a power park. Based on this very limited criterion for spacing, distances between 100 MW plants is likely to be not much less than 10 km. However, these results are preliminary, and environmental impacts of plumes in the intermediate-field environment may have more bearing on plant spacing than simple recirculation. The cumulative effects of wakes of individual plants in a power park grid may limit the number of plants in such a grid and the spacing of the plants within the grid. Until more is known about the ecological consequences of discharging bottom water mixed with surface waters at depth in the mixed layer, decisions regarding spacing from an environmental point of view remain uncertain. At this time, the most fruitful approach may be to examine the statistics of interactions among effluent plumes from a number of plants as they impinge on one another and other plants downstream. Models of and data on limited-area ocean circulation may prove helpful in this regard as estimates of spatial and temporal variability of transport are required to generate such statistics.

LARGE-SCALE AND WHOLE-BASIN ENVIRONMENTS

Assessments of large-scale impacts of multiple OTEC deployments in the Gulf of Mexico, or at other sites, require an understanding of large-scale ocean circulation. From a thermal resource point of view, it is also important to understand the dynamics of thermal resource renewal on large scales. Questions such as how many OTEC plants could be located in the Gulf of Mexico without exhausting the warm and cold water resources can be raised.

Answers to questions of large-scale mixing and transport will have to be found primarily by means of numerical models. A rather simple, but instructive, view of OTEC perturbations on the water in the Gulf of Mexico Basin was developed by Martin and Roberts.¹⁰ Their numerical model considered the Gulf of Mexico to be laterally averaged, that is, only vertical variations in temperature were included. They simulated the vertical redistribution of temperature in the Gulf due to deployments of 100 and of 1000 100-MW OTEC plants. The model included simulation of the mixed-layer thermodynamics throughout the year. The results of operating these numbers of OTEC plants within the Gulf for long periods of time (30 yr or more) indicate cooling of near-surface waters and warming of waters at depth in the vicinity of discharge. Preliminary results showed maximum temperature deviations from normal to be of the order of 0.1 °C and 1 °C for 100 and 1000 plants, respectively.^{10,11} This numerical model has a number of limitations including the lateral averaging, the specification of cold water renewal through the Straits of Yucatan, and the simulation of the discharges. Consequently, the actual numerical results should be viewed with some caution, until additional modeling eliminates some of the uncertainties associated with this simple model.

The circulation in the Gulf of Mexico is known incompletely. Estimates of the large-scale transport of OTEC effluents and of the persistence of thermal resource at certain sites in the Gulf depend on large-scale numerical modeling interpreted in terms of existing observational data and those being collected now for the OTEC program. A two-level, baroclinic, numerical model of the Gulf of Mexico was developed at the Naval Ocean Research and Development Activity (NORDA).^{12,13} This model, while developmental in nature, exhibited some of the main features of the Gulf including the Loop Current from the Straits of Yucatan into the Gulf and out the Florida Straits and the spinning off of eddies from the Loop Current into the Gulf. A recently initiated modeling effort for the Gulf in terms of OTEC needs has begun with Dynalysis, Inc. They plan to employ a 20-level model for circulation and temperature predictions in the Gulf. The effects of individual plants cannot be examined at the scales necessary for modeling basin-wide motions. However, the effects of OTEC power parks and other large-scale OTEC deployments in the Gulf are expected to be examined with such models. The Dynalysis' model is expected to employ rather sophisticated mixed-layer dynamics, and it is expected that the transport and mixing of effluent plumes from OTEC power parks might be simulated effectively in such a model.

It should be recognized that the large-scale numerical models discussed here require techniques at the leading edge of ocean modeling. The resolution of the scales of OTEC-induced perturbations and necessity for relatively long integrations forward in time represent real challenges to ocean modelers. Analysis of physical oceanographic data collected previously and gathered for OTEC purposes provides an important input for model development and evaluation^{14,15,16}. While exact simulation of the details of circulation in the Gulf of Mexico may be an unrealistic goal for OTEC

CLIMATIC EFFECTS

The possibility of sea surface temperature depression in ocean regions within which OTEC plants are operational means that changes to microclimate are also possible. While no definitive studies exist, it is clear that sea surface temperature depressions due to OTEC will be small, that is, on the order of $0.1\text{ }^{\circ}\text{C}$. However, temperature differences in this range are suspected to influence strongly microclimatological events. The difficulty of assessing climatic impact due to OTEC is, then, that of separating the effects of OTEC perturbations from those due to natural temperature variability. Since OTEC temperature perturbations are of the order of the noise in natural signals, this becomes a difficult task.

Piacsek *et al.*¹⁷ made estimates of the seasonal variation and annual average of the net heat flow crossing the ocean surface in the vicinities of Puerto Rico, Gulf of Mexico, and Hawaii. They assessed the effect of sea surface temperature variations, due to OTEC operations, on this net heat flow. Their calculations, based on bulk formulae, indicated that, for sea surface temperature depressions of about $1\text{ }^{\circ}\text{C}$, changes in sea surface heat flux of about 100% resulted. These were only preliminary calculations, and if applicable at all, apply to the situation of a cold surface wake downstream from an insulated OTEC plant. Large-scale surface cooling due to OTEC operation would significantly influence the atmosphere above that region such that formulae applied in the estimates by Piacsek *et al.* would definitely be brought into question. Moreover, simple heat budget calculations are made difficult by the fact that the advection of heat in and out of an oceanic region is difficult to quantify.

The question of CO_2 contributions to the atmosphere due to OTEC operations revolves around the advection of CO_2 -laden water from the deep ocean to the surface by the OTEC plant. Closed-cycle operation of an OTEC plant would probably preclude the immediate evolution of CO_2 gas at the ocean surface, as the CO_2 -laden water would be returned to the ocean in the effluent plume. However, calculations by Williams¹⁸ and others have indicated that if all CO_2 contained in deep water transported to the surface were evolved at the ocean's surface, the amount of CO_2 evolved would be about $1/3$ that released by a coal-fired plant of equivalent net power capacity. As this would appear to be an upper limit on the amount of CO_2 that could be evolved due to OTEC operation, and since significantly less CO_2 evolution is expected, it seems unlikely that OTEC will be a major contributor to atmospheric CO_2 .

Further, more detailed, considerations of climatic impacts are in order and will be undertaken. As additional information regarding OTEC impacts on the water side of the air-sea interface becomes available, efforts to assess the atmospheric side (and the exchanges) are expected to increase.

determination of OTEC induced modifications, at several scales, to the ocean environment. Predictions of physical modifications and of the transport and mixing of plant effluents are required for broader ecological assessments. Modifications to ocean temperature structure also impact power plant operations, and maintenance of the thermal resource must be accomplished in a manner consistent with environmental considerations.

Physical model studies at laboratory scales have provided data on the potential for resource degradation as a function of plant design and receiving water characteristics as well as the pathways and mixing of plant trajectories. Continuing physical model studies explore near-plant effluent behavior further for variations in upper ocean stratification and currents. Predictions of intermediate-field spreading and mixing are necessary to estimate impacts in the far wake of a plant and bear on spacing between plants. Analytical and numerical models for this regime are presently under development. The results of near-plant and intermediate-field effluent behavior provide the input and boundary conditions for models that simulate the large-scale transport of OTEC perturbations. Limited-area and whole-basin numerical models in development will be employed to address such large-scale modifications. Climatic impacts of OTEC are coupled to these larger-scale ocean modifications, and assessments of climatic impacts are dependent on the results from ocean models.

Finally, predictive models, both physical and mathematical, are only as good as the physics and data underpinning them. Physical oceanographic data in potential OTEC site areas are necessary both for characterization of the input parameters for many of the modeling efforts and for evaluation of the model simulations.

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ABSTRACT

Ecologically sound operations of projected Ocean Thermal Energy Conversion (OTEC) plants can be insured by careful attention to the marine environment during the design phase. This requires quality information from regions of potential OTEC interest. Currently, preliminary or actual surveys and laboratory studies are being conducted in the waters of Puerto Rico, the Gulf of Mexico, Hawaii, and Guam for potential moored OTEC plants and in the equatorial South Atlantic for proposed plant-ship operations to provide such benchmark and baseline data. These data plus existing archival information can be used to model effects of OTEC operations based on projected design schemes. Four major areas of concerns (1) redistribution of oceanic properties, (2) chemical pollution, (3) structural effects, and (4) socio-legal-economic; and 11 key issues associated with OTEC deployment and operation have been identified. In general mitigating strategies can be used to alleviate many deleterious environmental effects of operational problems as biostimulation, outgassing, etc. Various research studies on toxicity, biocide releases, etc., are under way or are planned to investigate areas where no clear mitigating strategy is available. A Master Plan listing procedures to be followed to identify and evaluate potential concerns at any OTEC proposed site is proposed for discussion and refinement in advance of any real OTEC test operations.

PURPOSE

The goals of this paper are to present a logical strategy for the evaluation and eventual monitoring at Ocean Thermal Energy Conversion (OTEC) sites or regions so that

- the effects of an OTEC plant on the environment, and
 - the influence of the environment on OTEC operations
- can be assessed.

This should result in information which can be used by engineers, designers, and planners to insure practical, safe, and efficient operations of any OTEC plant and provide sufficient justification for operational permits for OTEC plants from the involved regulatory agencies.

OTEC PROGRAM

Ocean Thermal Energy Conversion is a technology using the temperature difference between warm surface and cold deep water to produce electric power with a gas or steam turbine. An OTEC plant can be operated in either a "closed" or "open" cycle. In the closed cycle configuration, warm surface water heats an evaporator containing an appropriate working fluid, and the vaporized working fluid drives a gas turbine. After passing through the

the turbine. Once again, cold deep water is drawn up to condense the steam after passage through the turbine.

OPTIONS

At present there are three basic options proposed which use OTEC systems.

- Moored/electric - the OTEC plant is attached to the bottom with a combined mooring/electrical transmission cable. The OTEC plant is used to generate electricity which is connected to the power grid system via a submarine transmission line. In essence the OTEC plant is at a fixed geographic location, so its effects would be a point source in the horizontal plane and a line source in the vertical plane. With the present considerations of (1) 20°C Δ temperature as the limiting case for the commercial resource and (2) ocean engineering capabilities for size and mooring of potential OTEC plants; the depth of water for operations the moored electric OTEC plant is between 800 and 1500 M. Accordingly, the distance off-shore for the location of any potential OTEC plants would be a function of bathymetry or having the appropriate thermal resource in a designated range of depths of water. As the plant is moored its operations would come under the jurisdiction of the nearest nation regardless of the boundaries of any economic zone.
- Grazing/manufacturing - the OTEC plant is located on a floating maneuverable platform or ship. The OTEC plant is used to generate power which in turn is used to manufacture a product such as hydrogen or ammonia from sea water, or alumina or aluminum from raw material brought to the ship. For the grazing/manufacturing option, the commercial product is not electricity but some goods exported via surface ships to markets. The plant with its own motive power essentially grazes the thermal resource without regard to bathymetry, except that the water depth must be greater than the depth of the cold water pipe. Obviously this opens up a much larger area which can be used for OTEC. However, it vastly increases the area of potential concerns. With only a minimum depth limitation, the grazing plant could operate either in the economic zone of near-by nations or strictly in international waters. The environmental impacts of an operating OTEC grazing plant could be transferred by ocean currents into neighboring economic zones even though the plant itself was in international waters, thus potentially causing complex jurisdictional problems.
- Seaside/electric or manufacturing - this type of OTEC plant is land-based and the water is pumped to the generating plant either by pipelines along the sea floor, tunnels, or is delivered to the site as "waste" heat from a seaside power plant. Such a plant could generate power for the electrical grid or for manufacturing purposes as in the grazing option. This type of plant has the basic attributes of conventional seaside power plants so it would have the same environmental concerns.

ENVIRONMENTAL CONCERNS

The four major classes of environmental concerns and the key issues in these classes associated with OTEC deployment and operation are:

SCHEMATIC DIAGRAM OF CLOSED CYCLE OTEC POWER SYSTEM

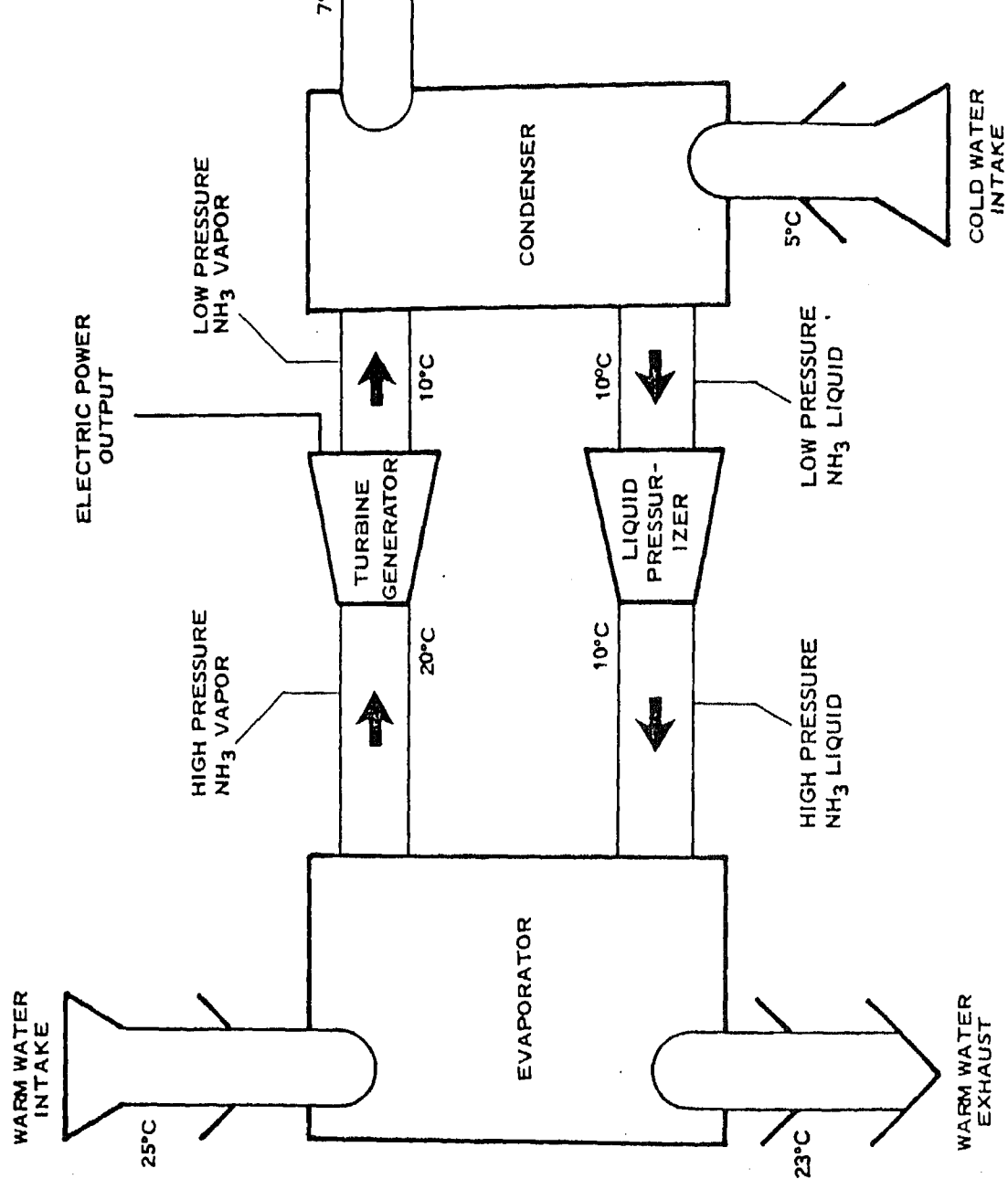


Figure 1

(from DOE/EDP 0006, March 1978)

Chemical Pollution
Biocides
Working fluid leaks
Corrosion

Structural Effects
Artificial reef
Nesting/migration

Socio-Legal-Economic
Worker Safety
Enviro-Maritime law
Secondary economic impacts

The potential changes in the oceanographic properties of sea water due to OTEC pumping operations are a major environmental concern. Because large amounts of cold, deep water and warm shallow water will be pumped to the heat exchangers, likely at some third depth; parameters such as temperature, salinity, density, dissolved oxygen, nutrients, carbonates, particulates, etc., will be modified by mixing with ambient ocean water in the vicinity of the eventual discharge. Discharges in the photic zone may cause biostimulation due to the increased nutrient contribution from the deep waters, with potential changes in either the size, relative abundance or species composition with respect to the resident marine population resulting in secondary effects on the food web. Displacement of sea water also could have toxic effects on ambient species by the introduction of trace chemical substances such as trace metals, organic decay products, etc., from other depths. Certain species, particularly those with low mobility, will be harmed by impingement/entrainment in the pumping system either by contact with the screens and walls of the pipe-heat exchanger system or by the pressure and temperature changes encountered in transit of the system from intake to discharge. Surface discharges may produce climatic effects by alteration of the air/surface water temperature ratio. Such an alteration, at sufficient scale such as in an OTEC park, could affect the microclimate by modification of locally generated winds and currents. Long-term operation of a large number of OTEC plants could result in reduced available heat due to the thermal extraction. Surface discharges also could enhance the release of CO₂ and other gases dissolved in cold deep waters with potential climatic effects for large scale operations. This is particularly true for open cycle systems where gases, even normally dissolved in the surface ocean, must be separated from vaporized sea water so that gas bubbles do not impede plant efficiency. Such gases will be vented into the atmosphere potentially modifying the local microclimate as discussed above. However, subsurface discharges below the surface mixed layer in the pycnocline could mitigate all or most of the potential problems associated with surface discharges.

Chemical pollution could result as functions of various OTEC plant operations and maintenance procedures. Of major concern are biocides proposed

operation. The major problem with biocides is the levels of concentration needed to impede biological growth in the system which unquestionably will affect organisms in the vicinity of the discharge. Furthermore, if chlorine is used as a biocide and ammonia as a working fluid, accidental combinations of these chemicals can produce compounds even more toxic to ambient organisms than the separate chemicals. Leaks of the working fluid of a closed cycle system also will pollute ambient ocean water. The effects and chemical fate of proposed working fluid leaks into sea water are not well understood. Ammonia, for example, is a nutrient in proper amounts and could stimulate marine growth complicating the biofouling problem. However, the excessive doses associated with a major leak is both toxic to marine and human life. Chemical pollution also will be produced by the corrosive effect of sea water passing through the heat exchanger system. Corrosion would produce metallic ions, and scale particles which could have direct toxic effects or long term effects through incorporation of corrosion products into the particulate food supply of marine organisms through the process of bioaccumulation.

The physical presence in the ocean of a structure the size of an OTEC system itself has an impact on the ocean. The structure of whatever configuration will become an attractive habitat for a wide range of organisms based on experience from artificial reefs. The long-term effects of the structure on the environment will depend on the types, size, and abundance of the organisms attracted to or attached to the structure and this will modify the local population. Regional effects on populations might occur by either interference with, or modification of, nesting habits or migration pathways.

The first three major classes of concerns chiefly dealt with impacts on marine life. However, there are human consequences of OTEC operations which are grouped here as socio-legal-economic issues. Worker safety is of prime concern regulated by the Occupational Health and Safety Administration (OSHA) and the Coast Guard for strictly marine occupational concerns. Potential work hazards are the chemicals used or produced by the OTEC system such as ammonia, chlorine, foul weather during marine operations, collision, and systems accidents. Because of the novelty of OTEC operations standard safety procedures will be augmented by procedures unique to OTEC. The siting of OTEC facilities either in international waters or where the downstream effects of OTEC operations might intrude into international waters, will raise the issues of international rights and responsibilities beyond those treated by conventional maritime law and treaties. At present the law of the sea is in a state of flux so that the resolution of potential international issues may be complicated and time-consuming. Probably multilateral agreements or treaties among concerned parties, as is done for fishing rights, may be the interim solution of potential legal problems which may impeded OTEC operations. Finally, the construction and operations of an OTEC facility may affect existing social and institutional structures. New jobs will be created and shore-based "boomtown" growth may occur with its associated impacts on housing, education, sanitation, etc. The electrical energy produced by OTEC plants may be transmitted to consumers either by

produce energy-intensive products, they will produce air/water emissions typical of those produced in similar land based industries.

The present and projected status of the resolution of these issues is listed in Table 1. Detailed discussion of these issues is found in the 1978 Environmental Development Plan (EDP) for OTEC.

PRESENT AND PROJECTED MONITORING PROGRAM

The monitoring strategies are designed for shipboard operations, manned platforms as well as instrumented buoys (Table 2). This program is to be integrated with those proposed by OTEC groups for bio-fouling and corrosion, and by NOAA for synoptic oceanographic parameters. An additional goal is to develop a packaged monitoring program which can be mobilized rapidly to aid in site selection for larger OTEC platforms (Fig. 2). Data collection and monitoring strategies will be done in view of compliance with NEPA and EPA, Corps of Engineers, Coast Guard, etc., regulations.

Specifically the program initiated pre-operational studies in four areas:

- o Hawaii - one site near Keahole Point
- o Puerto Rico - one site near Punta Tuna
- o Gulf of Mexico - regional survey using two station locations:
 - (1) west of Tampa
 - (2) south of Biloxi
- o South Atlantic - regional survey, 5-10°S, 20-30°W and affected zone.

In the areas considered for the moored OTEC option - Hawaii, Gulf of Mexico, and Puerto Rico - a program has been initiated to take background data before placement of any operating OTEC system in these areas. This is required to insure that baseline information is available to evaluate the effects of OTEC on the ambient environment and to provide environmental data useful in the design of the operating system. At this time, only attractive thermal regions are known with any certainty. It is premature, therefore, to pick exact sites for potential OTEC plants until knowledge of other important environmental siting factors is obtained. Accordingly, for the initial studies each thermal region is divided into subregions in which it is expected that the basic environmental conditions relating to OTEC are spatially homogeneous, although likely to vary seasonally. To characterize each subregion a reconnaissance benchmark is located. A benchmark is defined as a specific location, typical of a subregion, where serial data are taken and to which historical data may be referred. Because of the lack of serial, long term records of any kind in attractive thermal regions, we believe that the benchmark approach is more valuable in the long term than initiating broad regional surveys where variations in measurements may be attributed to site as well as time variability. Where substantial subregional variability is found, the benchmarks will be used as starting points for potential regional surveys. The intent of taking measurements at benchmarks is to provide data, at a specific location, which will form the basis, in conjunction with previously obtained data from the area, for defining longer term and more comprehensive environmental

Table 1

ISSUES, REQUIRED RESEARCH, AND PROJECTS

ISSUES	REQUIRED RESEARCH	Status of Projects	
		COMPLETED	CURRENT
OCEAN WATER MIXING	<ul style="list-style-type: none"> • Develop computer model to predict the impact of OTEC operations on oceanographic characteristics 	2	3
	<ul style="list-style-type: none"> • Establish baseline oceanographic data at potential OTEC test sites 	3	2
	<ul style="list-style-type: none"> • Characterize changes in oceanographic characteristics resulting from OTEC test operations 	2	2
	<ul style="list-style-type: none"> • Determine impacts of oceanographic changes on site-specific marine ecosystems 		4
IMPINGEMENT/ENTRAINMENT	<ul style="list-style-type: none"> • Search existing literature to determine extent of impact at similar ocean water pumping operations. 		2
	<ul style="list-style-type: none"> • Monitor impacts at OTEC testing sites and define factors responsible for attraction of organisms 		2
CLIMATIC/THERMAL	<ul style="list-style-type: none"> • Develop computer models to predict impacts of OTEC operation on micro- and macroclimate 	2	2
	<ul style="list-style-type: none"> • Characterize site-specific climatic impacts resulting from OTEC test module operations 	1	2
	<ul style="list-style-type: none"> • Determine potential increase in levels of atmospheric CO₂ resulting from OTEC operations 		
	<ul style="list-style-type: none"> • Determine potential microclimate effects of degassing during open cycle OTEC operations 		

Table 1 (continued)

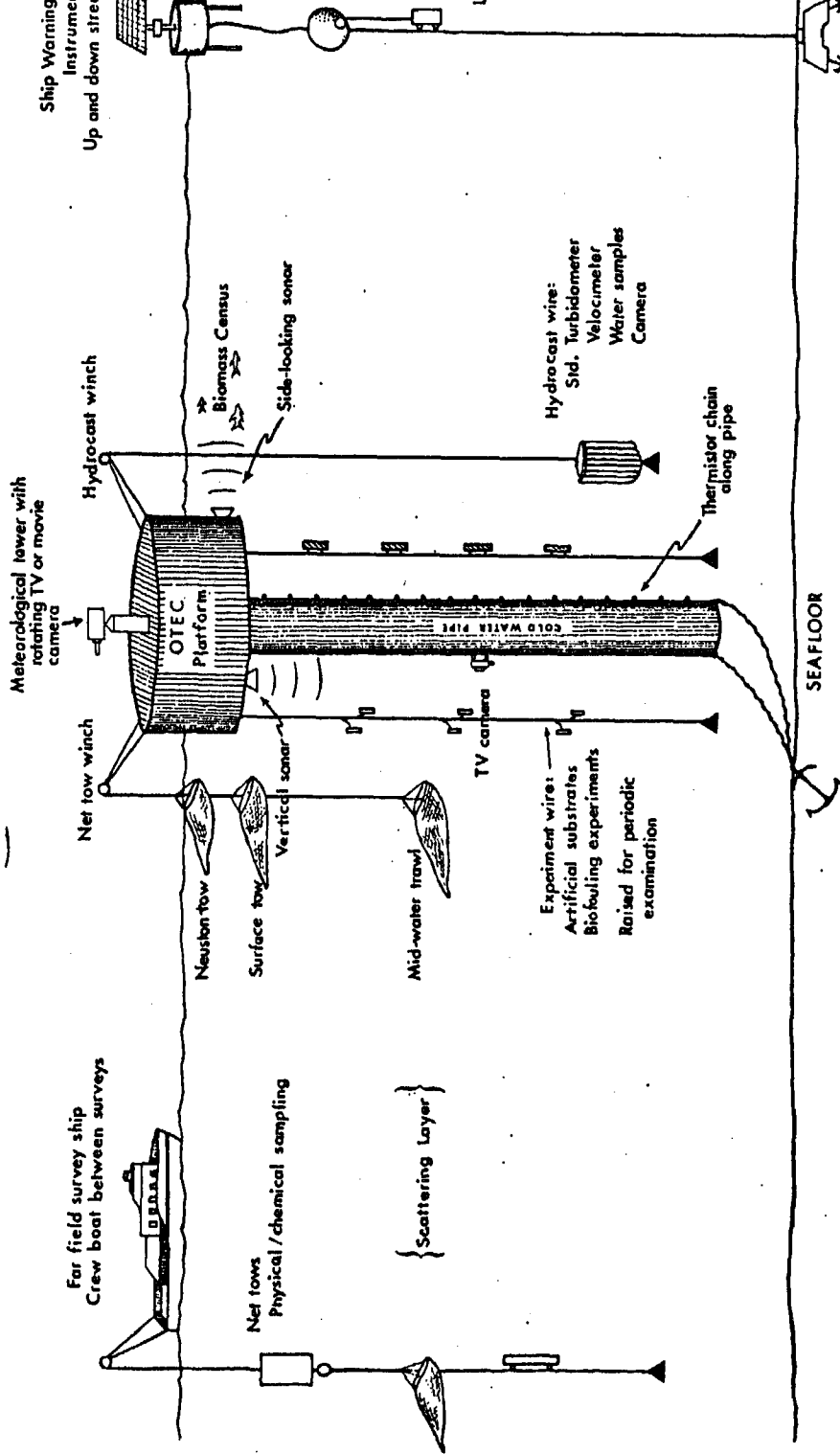
ISSUES	REQUIRED RESEARCH	Status of
		COMPLETED
BIOCIDES	<ul style="list-style-type: none"> • Survey existing literature to determine impacts of biocides on marine species • Monitor, sample, and characterize biocide discharges during OTEC testing operations • Conduct laboratory tests to determine the effects of varying levels of biocide use on marine ecosystems. 	
WORKING FLUID LEAKS	<ul style="list-style-type: none"> • Survey existing literature to characterize impacts of various levels of potential working fluid leaks on marine ecosystems. • Monitor, sample, and characterize the extent of working fluid leaks during OTEC operations 	
CORROSION	<ul style="list-style-type: none"> • Survey existing literature to determine effects on marine species of metallic element compounds discharged from heat exchangers constructed of various metals. • During OTEC testing operations, monitor, sample, and characterize metallic elements discharged and dispersed into ambient ocean water, and determine the impacts of these discharges on indigenous marine species. 	
ARTIFICIAL REEF TESTING/MIGRATION	<ul style="list-style-type: none"> • Define Factors responsible for attraction of organisms 	

Table 1 (continued)

ISSUES	REQUIRED RESEARCH	Status of Progress	
		COMPLETED	CURRENT
WORKER SAFETY	<ul style="list-style-type: none"> Develop worker safety programs for OTEC facilities using input from land based facilities using/producing the same chemicals 		1
	<ul style="list-style-type: none"> Develop a warning system for OTEC facilities to prevent collisions with other ocean vessels 		1
ENVIRONMENTAL MARITIME LAW	<ul style="list-style-type: none"> Conduct survey of international law of the sea applicable to OTEC operations; update biennially 	1	
	<ul style="list-style-type: none"> Conduct in-depth study of potential legal/institutional issues involving the particular site(s) chosen for OTEC operations 		
SECONDARY ECONOMIC IMPACTS	<ul style="list-style-type: none"> Assess the secondary impacts (e.g., land use, air/water emissions, solid wastes) associated with construction of OTEC plants 		1
	<ul style="list-style-type: none"> Assess the socioeconomic impacts of OTEC development Assess the ecological and secondary impacts of electricity transmission Survey existing literature to characterize air/water emissions expected to be encountered in the production of chemicals at OTEC plants; develop applicable control technologies 	1	1

Satellite with thermal sensors

Fly-by with aircraft
Infra-red photography
Conventional photography
Thermal scanners



Not to scale

Figure 2-OTEC

Table 2

PROPOSED ECOLOGICAL MONITORING STRATEGIES

		Time Schedule
STEP I	- PRE-OTEC site occupation studies; background sampling of significant ecological and chemical parameters in conjunction with a literature review to define pre-operational environmental conditions. Sampling from survey ships or from fixed moorings Sampling frequency bi-monthly initially for one year, further sampling frequency to be determined by experience	Initiated FY 78 Puerto Rico, Gulf of Mexico South Atlantic (operated, LBL monitored)
STEP II	- Non-interference with Platform Operations No permanent work space on platform Sampling equipment self-contained and transported to and from site Sampling frequency a function of operations schedule All analyses done on beach	Initiated FY 79
STEP III	- Limited interference with platform operations Limited permanent work space on platform Sampling equipment and some analytical equipment on site Most analyses done on beach	Plan FY 79 RFP late FY79 Operational FY (Contractor operated, monitored)
STEP IV	- Limited interference with platform operations (Crane operations, etc.) Permanent work space in container/vans Power/water from platform but with backup systems	Plan FY 79-80 (Experience from II) RFP late FY 80

TABLE 2
(continued)

STEP IV (continued)	<u>Operations Van</u> (sensor packages on buoy)	<u>Time</u> Operational (first unit) Additional
	A. Wet Lab - sample preparation - gross equipment repairs B. Dry Lab I - instruments/analyses/electronic repairs C. Dry Lab II - data reduction/storage/remote monitors	
	<u>Storage Van</u> (not applicable to buoy)	
	A. Wet Storage - nets, over the side gear B. Dry Storage - equipment, paper C. Sample Storage - refrigerator	
	Real time operations with rotating permanent technicians Essentially all analyses and data processing done on site	

sites are given in Tables 3 and 4. At each benchmark, a current meter array will be deployed to complement current profiler runs during station operations. Satellite data, when available, will be used to assist the interpretation of data from the arrays. Because of costs and reliability factors, measurements for the initial surveys will be mainly from survey ships rather than from instrumented buoys. The survey ship will occupy each benchmark site bi-monthly for a minimum of three days with augmented sampling every four months. Sampling at each station occupation is designed to give, at a minimum, day-night variations as well as bi-monthly variations for the biologically significant parameters. Parameters sampled bi-monthly are thought to have variations which may be detected at that frequency. Parameters sampled every four months are thought:

- (1) to have less variation annually; or
- (2) to have potential but unresolved significance to OTEC.

The augmented sampling every four months also is done to develop optimal measurement and sampling techniques for parameters which may become routine during future site occupations. Upon completion of the initial study (actually, during the surveys) the sampling frequencies and choice of parameters will be re-examined. Results from augmented samplings, from serial samplings and historical data reviews will be used to design subsequent site data collections.

MASTER PLAN - OUTLINE OF CRITICAL PATH

Given a candidate site or region, the following gives a proposed outline of the ideal progression of steps to be taken in the evaluation of the environmental concerns for that site or region. It is assumed that the primary selection of sites is a policy function of OTEC headquarters. The procedures presented here are designed to be applicable to any candidate site or region to insure the quality and uniformity of information with respect to scope and kind available to regulatory agencies, policy makers, engineers/designers, concerned citizens groups, etc. However, we realize that each site or region is to some degree unique with its own characteristics not found elsewhere. Accordingly the suggestions here are to be considered only as a minimum, with any site or region specific information to be included where applicable.

PHASE I - Pre Go-Ahead Decision

● LITERATURE SURVEY AND OTHER PREVIOUS WORK

Published and unpublished literature, pertinent to the selected site or region, will be compiled and searched for data of potential interest to OTEC. Experts in the area will be identified. Agencies, institutions, schools, etc., with data bases, collections, etc., will be identified and contacted with the availability of their information ascertained.

● ORGANIZATION INTO A STANDARD FORMAT

All data obtained from Step I will be collated and displayed on a uniform base. This includes base maps of appropriate scale, uniform graphics and tabular material where appropriate. Such material and non-standard material such as photographs, keys to collections, etc., will be compiled into Source Volumes for the candidate area or region.

STATION OPERATION

PROFILER VERTICAL PROFILES OF HORIZONTAL CURRENTS

HYDROCAST DISCRETE SAMPLES AT DEPTH OF:

- A. Temperature
- B. Salinity
- C. Dissolved Oxygen
- D. Nutrients
- E. Phytoplankton

STD VERTICAL PROFILES OF SALINITY, TEMPERATURE

NET TOWS BIOLOGICAL SAMPLES

XBT VERTICAL PROFILES OF TEMPERATURE TO 750 M

CURRENT METER ARRAYS DISCRETE MEASUREMENTS OF HORIZONTAL WATER
CURRENTS AT DEPTH

TRANSMISSOMETER VERTICAL PROFILES OF LIGHT TRANSMITTANCE

CLASS OF STATIONS

PRIMARY

Occupied in locations of prime OTEC
interest - sampling frequency to
ascertain diurnal changes

3 DAY DURATION

2 Deep Hydrocasts
2 Shallow Hydrocasts
2 Oblique Net Tows
4 Current Profilers
12 XBT
4 STD

CURRENT PROFILER

Occupied to determine spatial
variability of current regime

2-1/2 HOUR DURATION

1 Current Profile

TABLE 4

ECOLOGICAL/CHEMICAL PARAMETERS

<u>PARAMETER</u>	<u>STATION OPERATION</u>	<u>STATION FREQUENCY</u>	<u>SAMPLING FREQUENCY</u>
Temperature	hydrocast	bi-monthly	all hydrocasts
Temperature	STD, XBT	bi-monthly	4 STD, 12 XBT
Salinity	hydrocast	bi-monthly	all hydrocasts
Salinity	STD	bi-monthly	4 STD
Water Currents	current meter	continuous	one per 30 minutes
	profiler	bi-monthly	4
Light transmittance	transmissometer	bi-monthly	2 traces per cruise
Dissolved Oxygen	hydrocast	bi-monthly	2 casts
Orthophosphate	hydrocast	bi-monthly	2 casts
Total Phosphate	hydrocast	every 4 months	2 casts
Silicate	hydrocast	bi-monthly	2 casts
Nitrate	hydrocast	bi-monthly	2 casts
Ammonia	hydrocast	every 4 months	2 casts
Urea	hydrocast	every 4 months	2 casts
Total Nitrogen	hydrocast	every 4 months	2 casts
Alkalinity	hydrocast	yearly	2 casts
Trace Metals	hydrocast	yearly	1 cast
Chlorophyll/Phaeophytin	hydrocast	bi-monthly	2 shallow casts
ATP	hydrocast	every 4 months	2 shallow casts
Phytoplankton census	hydrocast	bi-monthly	1 shallow cast
C ¹⁴ uptake	hydrocast	every 4 months	1 cast
POC	hydrocast	yearly	1 cast
DOC	hydrocast	yearly	1 cast
Zooplankton census	net tow	bi-monthly	6 tows

drawn from data of similar quality.

- CONSTRUCTION OF ADEQUACY MATRIX

Data of comparable quality will be examined as a function of quantity of measurement, frequency and time history of sampling by a panel of experts to determine for each critical area whether sufficient data exists for a preliminary decision on the acceptability of the site or region. In this step data gaps will be identified.

- PRELIMINARY DECISION

On site/region as a candidate for OTEC operations. Options: a) *Definite No* - overriding negative factors; b) *Qualified No* - Negative factors present which may be mitigated by design strategies; c) *Ambiguous* - potential negative factors or conflicting data which cannot be resolved by information to date; d) *Neutral*; e) *Qualified Yes* - positive factors with ambiguous unknowns.

- POLICY DECISION

Yes/No on continuation of consideration of site/region as candidate for OTEC operations. If yes-proceed.

PHASE II - Pre-Operational

- INITIATE EIA/EIAS FOR SITE/REGION

Based on the current level of technological development of OTEC. Begin fulfilling the legal requirements for eventual permitting of the site.

- DESIGN CORRECTION STRATEGIES

Based on the adequacy matrix design a measurement and assessment program which eventually will provide information to reduce the level of uncertainty about site/region.

- DESIGN SERIAL PRE-PLANT MONITORING STRATEGIES

In conjunction with correction strategies, design a measurement and assessment program which will augment existing or begin serial data collections required to provide sufficient background information to access impact of any future OTEC operations at the site.

- INITIATE ONE YEAR PILOT PROGRAM

At site to ascertain environmental variability. As it is unlikely that sufficient data exists on annual and seasonal variability at any given site, the initial sampling frequencies must be estimated for most parameters. The intent of this program is to sample at high enough frequencies to justify the choices used in the long-term monitoring program. This program also will be used to test new or improved methods of sampling and to verify the utility of other parameters to access the environmental concerns.

- DESIGN LONG-TERM MONITORING/ASSESSMENT PROGRAM

As a result of the previous work and the one-year variability study, develop a long range monitoring/assessment program which will lead to compliance with regulatory requirements and facilitate production of the appropriate EIA/EIS.

be operated from the actual plant. The primary purpose of this program is to monitor the intakes and outputs of the plant as well as the near plant environmental conditions.

- POLICY DECISION

Request OTEC operations at site/region

- OBTAIN COMMENCEMENT PERMITS

Submit final EIA/EIS for action by appropriate regulatory group.

AFTERWORD

As the initial OTEC test module contract has just been let (September, 1978) it is too early to determine if the environmental strategies advocated here need to be augmented or modified greatly. Unquestionably strong interactions among environmental groups, regulatory agencies, designers and engineers, and DOE will be required to insure the success of the OTEC environmental program in attaining the goal of ecological compatibility and economical viability for OTEC systems.

To insure continuity among stated DOE program positions and interim reports of this nature, portions of existing documents such as the OTEC Program Summary (1976 and 1977) and the OTEC Environmental Development Plan (1977 and 1978) have been quoted here exactly or with minor modifications.

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I. INTRODUCTION

Since 1976 The Radiation Laboratory, under sponsorship from DOE, has been studying the effects of large horizontal axis wind turbine generators (WTG) or windmills on the performance of various electro-magnetic systems, and the present paper summarizes our investigation to-date.

To a receiver of electromagnetic signals in the vicinity of a WTG, the rotating blades act as a time varying multipath source. As a result of the scattering from the blades, the total signals received are generally amplitude and phase (or frequency) modulated, the former being more dominant. This extraneous modulation of the desired signals, if sufficiently strong, can adversely affect the performance of an electro-magnetic system. The degree and nature of the interference will depend on the signal transmission and reception methods used by the system, and the electromagnetic scattering characteristics of the WTG blades.

We have carried out a wide-ranging theoretical and experimental investigation of the electromagnetic effects of large horizontal axis WTGs on the performance of TV and FM broadcast reception, microwave communication link and air navigation systems. In the following sections we summarize the work done in the different areas and highlight the significant findings.

II. TV BROADCAST RECEPTION

Theoretical considerations of the electromagnetic scattering from idealized model of a WTG blade showed that the rotating blades can pulse amplitude modulate the total signal received in its vicinity, and a simple signal analysis of the basic detection process of a TV receiver indicated that such extraneous modulation, if sufficiently strong, could produce video but not audio distortion on reception.

Fig. 1 is a sketch of a typical experimental set-up near the operational NASA/ERDA 100KW WTG at Plum Brook. Video distortion on TV channel 43 was observed at a distance of about 0.5 Km from the WTG, when a typical directional antenna received the direct signal through its mainbeam and the signals specularly scattered off the WTG blades through its side lobe. The total received signal (on channel 43) as a function of time is shown

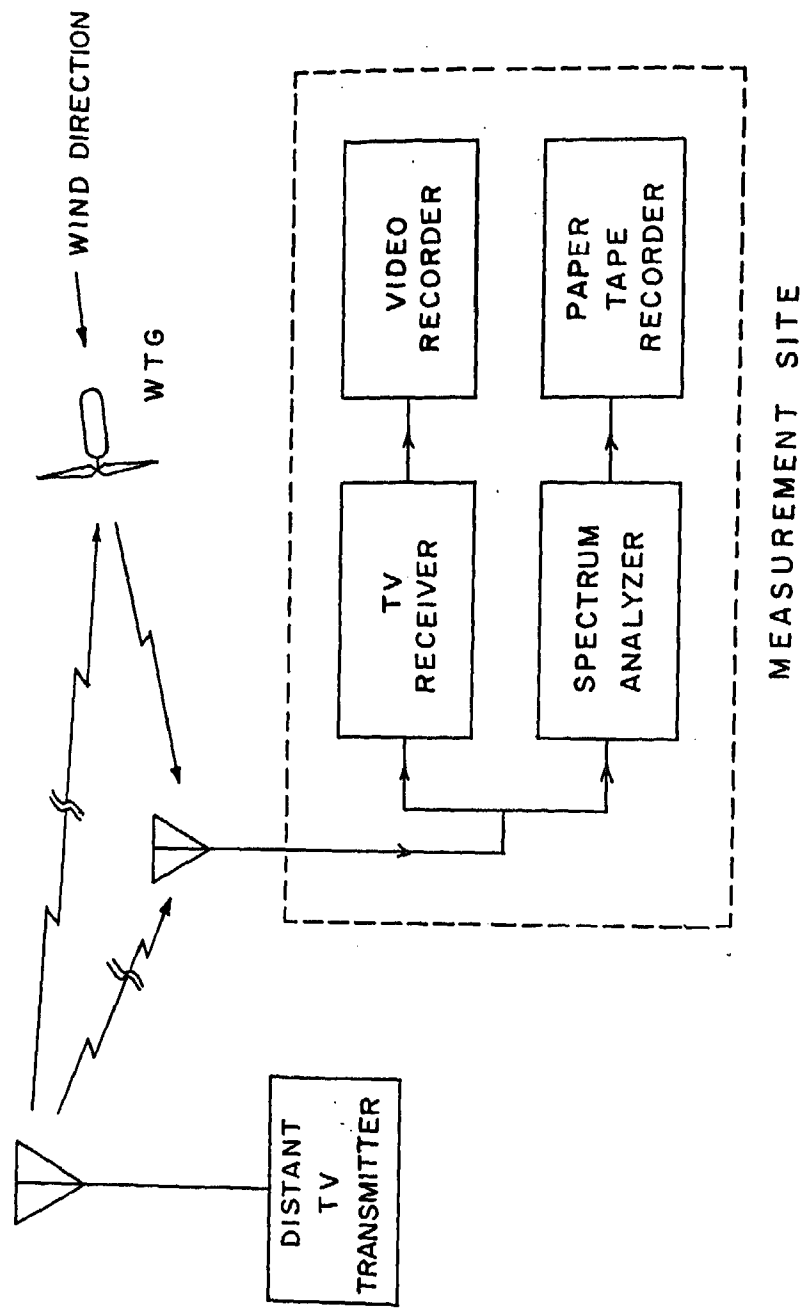


Figure 1. Schematic diagram of a typical on-site experimental set-up.

with the pulses. For the case shown in Fig. 2, the nature of the observed distortion was a horizontal jittering of the received picture. For cases when the forward-scattered signals from the WTG were directed to the test receiver, the distortion appeared in the form of intensity fluctuations of the received picture.

A number of tests were performed in a laboratory environment where the interference to the reception of TV signals was studied under conditions simulating those experienced near the operational WTG at Plum Brook: the direct signal was combined with an artificially-generated multipath signal so that the total signal input to the test receiver was amplitude modulated by a repetitive pulse having a width and shape approximating those observed at Plum Brook. The laboratory tests established a modulation threshold defined as the largest value of the amplitude modulation index (m) of the received signals for which the resulting video distortion is still judged acceptable for short periods of viewing. This threshold value m_0 (~ 0.15) has been found to be substantially independent of the ambient signal strength.

Using the above modulation threshold, a theory was developed to compute the interference region about a windmill for any given TV transmitter, and the results are in good agreement with those obtained from on-site measurements using the operational WTG. Fig. 3 shows the interference region for TV channel 52 of a WTG with MOD-1 blades.

In general, it has been found that a horizontal axis windmill does produce video distortion of TV reception in its vicinity, and the upper UHF TV channels are particularly vulnerable. The maximum distance from the WTG at which adverse interference may occur is a function of the windmill blade dimensions, material, and orientation, and the receiving antenna characteristics. The size of the interference region decreases as the TV channel number is reduced.

III. FM BROADCAST RECEPTION

Laboratory simulation techniques were used to study the interference to FM broadcast radio reception by artificially modulating the received signals with a pulse similar to that produced by the WTG. The interference was assessed by listening to the quality of the audio reproduction as a function of the ambient level of the signal and applied modulation index. The test receiver was a typical stereo receiver used in automobiles. When the ambient level of the input signal was high (signal-to-noise ratio, $S/N \gtrsim 15$ db), no distortion was found until the modulation index (m) reached about 0.73; even with a weaker signal

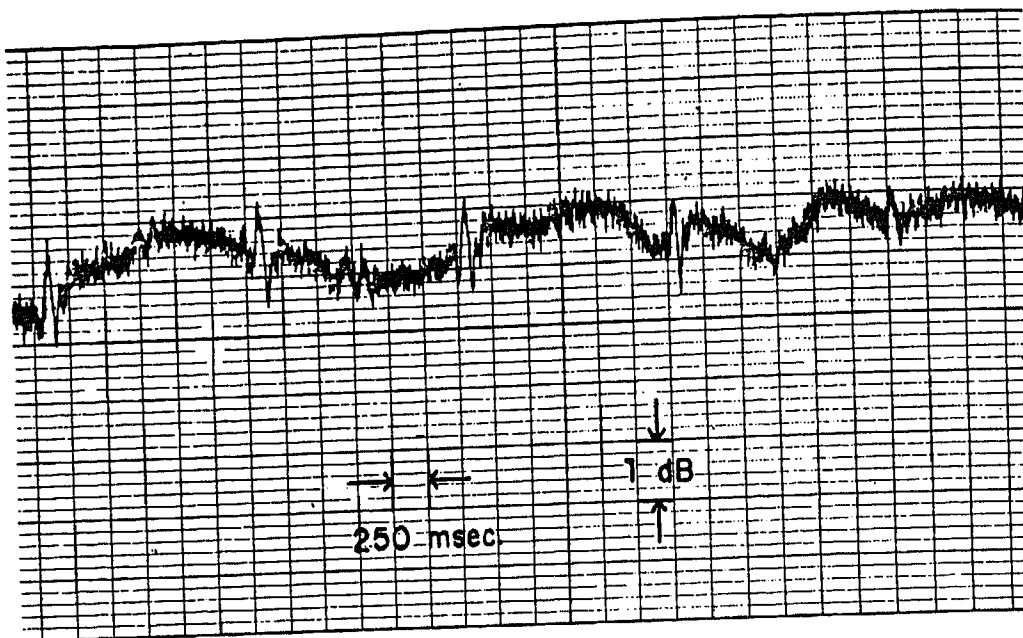


Figure 2. Received TV Channel 43 signal as a function of time near the NASA/ERDA 100 Kw WTG at Plum Brook. Blade rotation frequency=20 rpm.

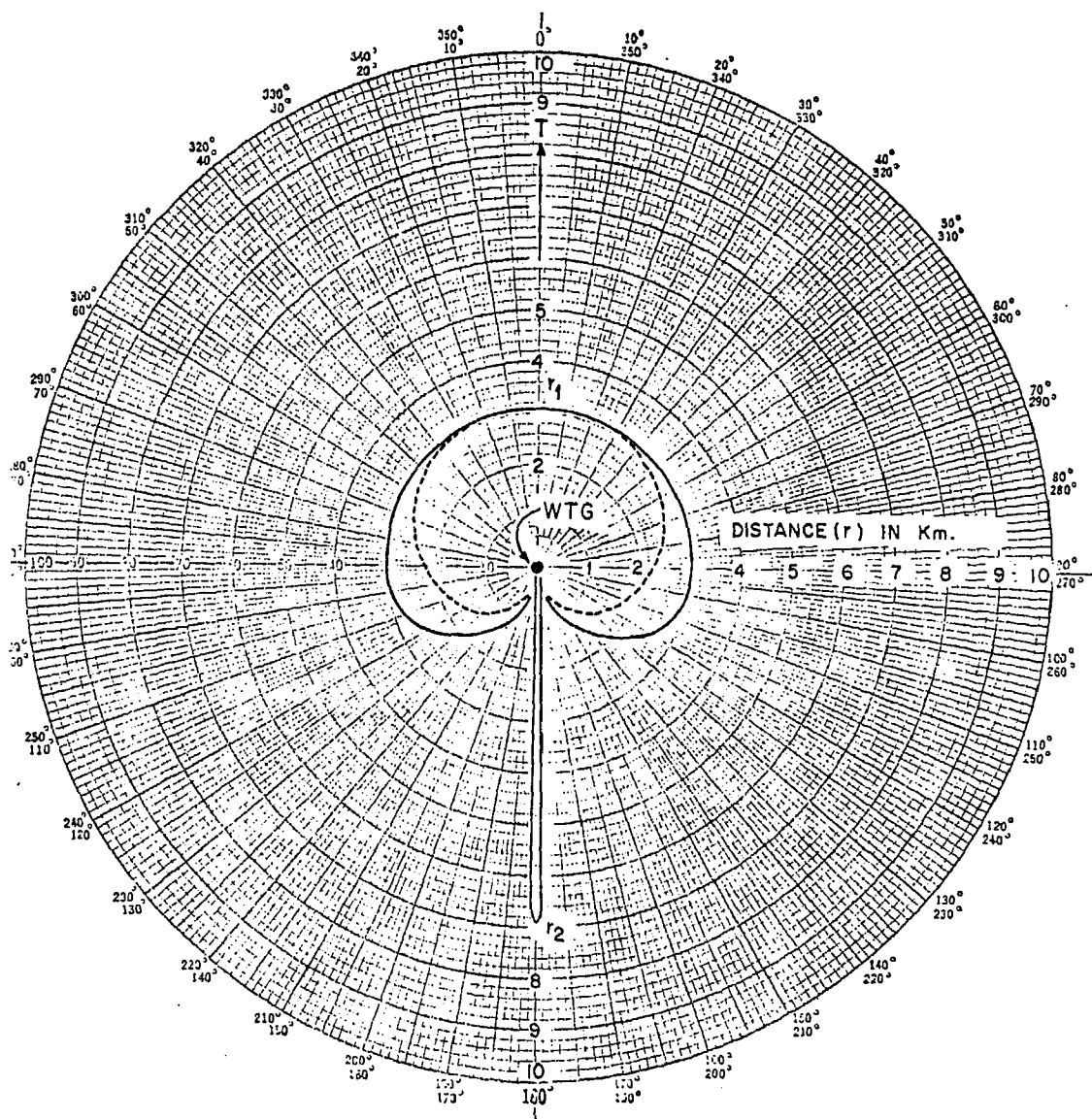


Figure 3. Interference region of a WTG with MOD-1 blades for TV Channel 52. Transmitter distance=120 Km.

— accurate graphical method,
 ----- approximate method.

ing amount of frequency hiss superimposed on the desired signal to FM radio reception imply that the effects of WTG interference to FM radio reception will be negligible except possibly within a few tens of meters of the WTG, and even then the audio distortion will be perceptible only if the WTG and the receiver are located in a region of low signal-to-noise ratio for that particular FM station.

IV. MICROWAVE COMMUNICATION LINK SYSTEM

The possible effects of a WTG in the vicinity of the repeater station of a typical microwave communication link (TD-) system used by the telephone companies were investigated theoretically. Using the threshold value for the interference to the desired RF carrier signal ratio established by the telephone company [1], and a knowledge of the signals scattered by the rectangular plate model of a static windmill blade, the concept of a forbidden zone around a microwave link receiver was developed, the zone being that where the placement of a windmill could produce unacceptable interference. The shape of the zone is primarily determined by the radiation pattern of the receiving antenna; its size is proportional to the equivalent scattering area of the WTG blade, and inversely proportional to the RF carrier wave length and the specified threshold value of the interference signal relative to the desired signal at the receiver. A typical forbidden zone of a 4 GHz microwave link receiver using a 8-foot parabolic dish antenna is shown in Fig. 4.

The effects of the blade rotation on the detected signal have been qualitatively assessed by examining the detection of the desired signal in the presence of the time varying modulation produced by the WTG. It is found that the blade rotation produces a frequency smearing of the received baseband signal energy, with the maximum frequency of smear depending on the blade size and orientation, and its rotation frequency. For a MOD-O blade this maximum is less than the FDM (Frequency Deviation Multiplex) bandwidth of the telephone channel. The degrading influence of the smear depends on the amplitude of the scattered signal at the receiver relative to that of the desired signal, and for a WTG outside the forbidden zone it would not appear that the blade rotation will produce significant interference effects.

V. AIRCRAFT NAVIGATION SYSTEMS

The VOR (Very high frequency Omni Range) and DVOR (Doppler VOR) systems are extensively used [2] for (commercial) aircraft navigation over the continental United States, and throughout

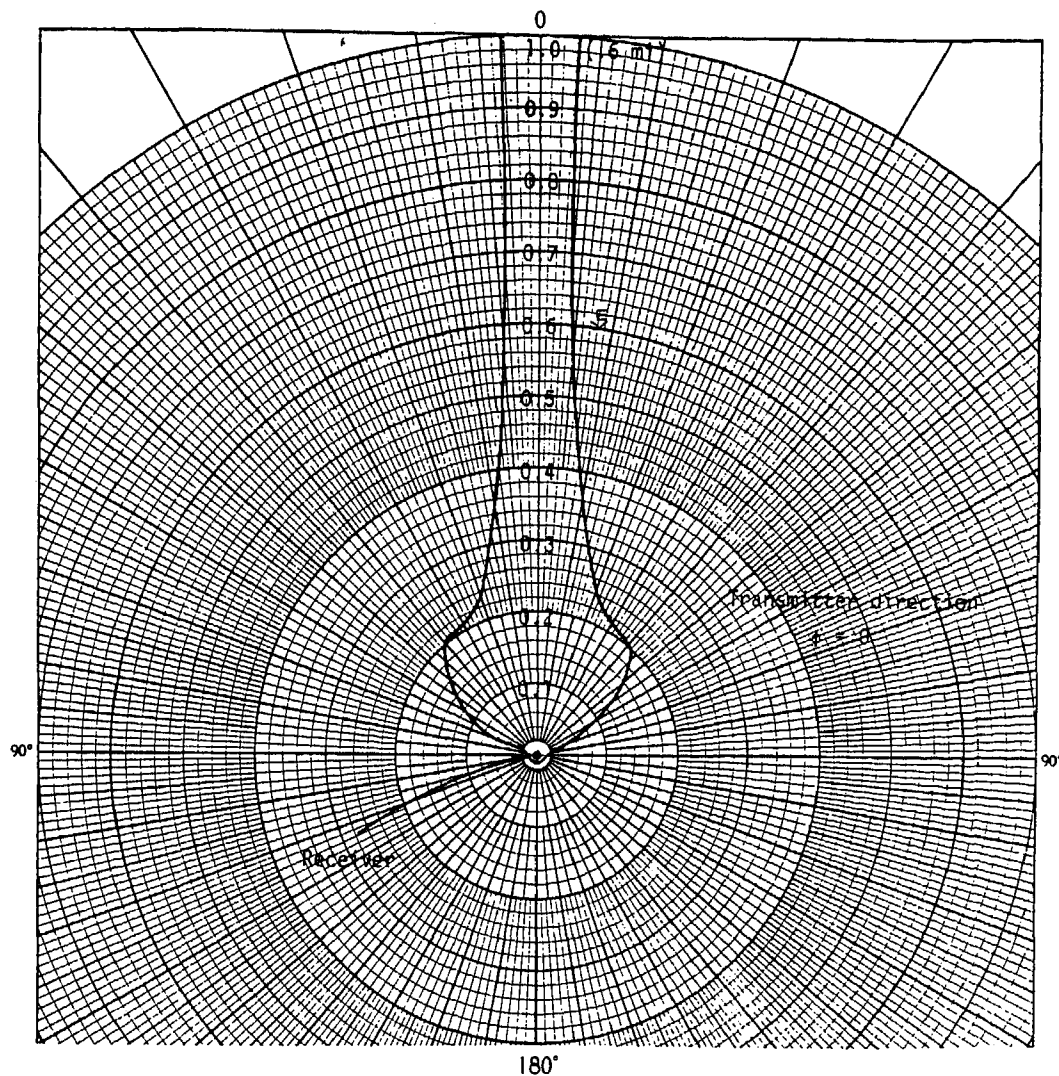


Figure 4. Forbidden zone of a 4 GHz microwave link receiver using a 8-foot parabolic dish antenna. Threshold of interference to carrier signal = -40 dB.

of these two systems. The analysis of the direct and windmill-scattered VOR (DVOR) signals at an aircraft and then using the detection characteristics of the receivers to estimate the resulting error in the predicted aircraft azimuth. The analytical procedures employed were logical extensions of those which the FAA has found acceptable in the case of static scatterers. The significant finding is that the stationary WTG blades produce more errors than the rotating ones. On the basis of the theory developed, some estimates of the error produced by a common windmill have been obtained. The results indicate that in choosing a site for WTG in the vicinity of VOR (DVOR) system it is sufficient to consider only the scattering effects of the stationary windmill. It therefore follows that the siting of a WTG can be carried out according to the standard guidelines established by the FAA [2].

VI. CONCLUSIONS

The interference produced by horizontal axis wind turbine generators on a number of electromagnetic systems has been identified and quantified. The interference to TV reception has been exhaustively studied, and a method has been developed to approximate the interference region of a WTG. This can be used to estimate the effects of a WTG on TV reception and thereby establish minimal criteria for the siting of such a machine. No significant interference to FM broadcast reception has been found. The performance of a repeating station of a typical microwave communication link system located in the vicinity of a WTG has been analyzed and guidelines have been developed which can aid in siting a WTG so that it produces minimum impact on the link system performance. Studies of the interference to two specific air navigation systems (VOR and DVOR) indicate that no significant degradation in the performance of these systems should occur if the WTG is sited according to the standard guidelines established by the FAA. Detailed descriptions of the studies are given in [3, 4, 5].

Currently we are studying the TV interference produced by vertical axis windmills, the manner in which the polarization of the transmitted and received fields affects the interference observed, and the possible interference with navigation systems like ILS, LORAN-C and Omega.

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ABSTRACT

The environmental impacts of wood energy conversion result from harvesting and transportation of the wood and construction and operation of the conversion facility. The major impacts are reviewed with an emphasis on industrial uses of wood energy. The major impacts are related to harvesting effects on soil nutrients, long term productivity of the forest and the competition which may develop for the forest resource. Air pollution and other plant-related impacts can be of local significance. Regional socio-economic benefits can accrue from wood energy use. Impacts are generally manageable and are unlikely to prevent expansion of wood energy use.

INTRODUCTION

This paper considers the environmental and socio-economic implications of the use of wood for energy in industrial and utility applications. The emphasis is on the combustion of wood in industrial boilers, using a 50-megawatt electric generation facility as an example. The environmental implications of other large-scale wood energy facilities would be similar.

Wood combustion is a relatively well understood technology with a long history in both domestic and industrial applications in the United States. Recent shortages and high prices of oil and natural gas have provided an impetus for rapid growth in domestic and industrial wood energy use, and an increasing interest among rural and small utilities in wooded regions of the country. Although wood combustion is not new, some of the environmental consequences have previously been ignored because of the small scale of use. Large-scale wood energy use gives rise to a diverse set of environmental impacts. This paper highlights the major areas of environmental concern and indicates the major research problems that need to be addressed.

in four parts

- Wood harvesting
- Wood transportation
- Conversion plant construction
- Conversion plant operation

Wood Harvesting

Wood for industrial energy facilities can be obtained from four sources: mill residues, energy plantations, logging residues, and harvesting low-quality wood. Mill residues can be obtained at relatively low cost where they are a waste product from wood industries; their use entails no additional procurement impacts beyond transportation. Burning wood residues frequently reduces environmental impacts associated with their disposal. Mill residues however are already heavily used and those that are available are quickly being used in the wood industry so that it is unlikely that they will provide a major source for the expansion of wood energy use.

Energy plantations are unlikely to be significant in the near future. Their environmental impacts will be generally similar to those of other harvesting operations although the increased frequency of harvest and more intensive use of the soil will tend to accentuate some of the impacts described.

The major source of wood for energy will be logging residues and harvested low-quality wood. Because the final or intermediate fuel product is wood chips, and because there are cost advantages in onsite chipping of all of the above-ground portions of the felled trees, the environmental impacts of whole-tree chipping must be considered.

The major environmental impacts of harvesting fuelwood are:

- soil damage and erosion
- hydrologic impacts
- sediment transport and deposition
- nutrient budget impacts
- chemical water quality impacts
- residual stand damage
- regrowth
- wildlife impacts
- socio-economic impacts
- aesthetic and recreation impacts

These impacts are highly interrelated, often site-specific, and very dependent upon the management of the harvest and type of equipment used. We shall not attempt to assess these impacts here but will summarize the state of knowledge and point out areas where further research is needed.

Soil compaction and disturbance are a precondition for accelerated soil erosion. Most soil damage occurs as the result of skidding and to some extent through felling, especially when feller-bunchers are used. Whole-tree chipping operations are not significantly different from traditional logging, except that feller bunchers are used more frequently. There is a substantial body of knowledge on the soil damage associated with different equipment and cutting practices that is applicable to impact assessment (see for example, EPA 1973, Nyland 1976, Biltonen et al. 1976, Zasada and Benzie 1975). Soil erosion depends not only on soil damage but also soil type, rainfall, and angle and length of slope. Soil erosion has been the subject of substantial research by the Soil Conservation Service and others and is now relatively well understood, such that reasonably good impact statements can be made.

There are two areas in which research is especially needed. One is in the use of lighter, smaller machines, such as those in use in Scandinavia, which have the potential for reducing soil damage. The second is in the economic and educational aspects of the use of sound soil conservation practices, especially among small forest landowners and small independent contractors.

Hydrologic impacts

The relationship between runoff and forest practices has been understood longer and has been more thoroughly researched than any other environmental impact of harvesting. Harvesting noncommercial wood for fuel, whether by selection or clear-cutting, is not significantly different in its impact on runoff from traditional forestry operations. Whole-tree chipping removes most of the slash, which will modify rainfall impact slightly, but probably only until regrowth occurs. Some selected whole-tree chipping sites should be monitored and stream flow data should be obtained in the more remote areas that may come into production as wood use increases. In general, however, assessment of hydrologic impacts is quite straightforward, and there is a substantial body of knowledge on hydrologic impact management (see Hornbeck 1973, Likens 1977, Sopper and Lull 1975, Megahan 1976).

Sediment transport and deposition

Soil erosion leads to sediment transport in streams and subsequent deposition downstream. This is a major pollution problem resulting from forest harvesting. It has been well-studied and guidelines have been developed for impact assessment and control (EPA 1973). Whole-tree chipping for fuel wood will affect sediment transport inasmuch as it affects soil damage and runoff, but it does not present any special research problems.

wood, will remove substantial amounts of nutrients from the forest ecosystem in short time periods. In addition to the boles, whole-tree chipping operation will harvest the tops, branches, and leaves (slash), and result in approximately a 30 to 50 percent greater harvest yield. More important, the slash contains a disproportionately high nutrient content so that the nutrient loss will be higher than the proportional increase in biomass removal. The losses of organic matter and nutrient through whole-tree chipping of fuel wood presents the largest single problem in the environmental impact assessment. Studies on this subject are few and because of the recent introduction of whole-tree chipping in the United States, none are long term. A review of six of the papers on the subject revealed little consistency with respect to nutrients selected for study, magnitude of losses or inputs, methods of analysis, or conclusions (see Boyle et al. 1973, Hornbeck 1977, Jorgensen et al. 1975, Malkonen 1973, Weetman and Webber 1972, and White 1974).

There are very few good long-term forested ecosystem nutrient studies such as the Hubbard Brook Study (Likens et al. 1977), and even that study is of limited application to whole-tree chipping of noncommercial wood for fuel. Some research is in progress by the U.S. Forest Service and elsewhere, but if whole-tree chipping for fuel wood or other purposes is to become an important forest practice, then a major program of research must be undertaken.

Chemical water quality

Whole-tree chipping removes more nutrients than traditional logging but the removal of slash also sets in motion a chain of events--increased light, higher soil temperatures, increased microbial activity, increased nutrient release--that can lead to the increase of nutrients in stream flow. It is possible that this could constitute a nonpoint source pollution problem (EPA 1973, Likens 1977). Because there have not been any long-term forest nutrient budget studies where whole-tree chipping has been used, impact assessment is difficult and further research is essential.

Residual stand damage

Skidding and, to a lesser extent, felling during thinning or selection cutting invariably cause damage to the residual stand. The magnitude of this damage depends upon the site, equipment used, and the skill and motivation of the operator. Nyland (1976) and other studies indicate that the amount of damage can be very high even when the logger has received special instructions and is presumably well-motivated. The cost of the damage in terms of the loss of potential timber growth varies with the species. Residual stand damage is a very important impact because, in many cases, the silvicultural (and economic) justification for harvesting noncommercial wood for fuel is the

potential improvement to the residual stand. Residual stand damage, for whatever reason, could make many fuel harvesting operations uneconomic.

Some equipment, such as the feller buncher, is relatively new in many areas and may help to mitigate adverse impacts. There also appears to be a need for smaller, lighter equipment, especially in hilly areas such as New England. Research and development in this area should include evaluation of Scandinavian machines and methods.

Regrowth

The vigor and species composition of the regrowth depends upon the extent of cut, soil damage and nutrient losses as well as other site-specific factors. Regrowth holds nutrients that might otherwise be lost to the ecosystem and impact streams (Likens et al. 1977). Regrowth appears to be an important index of a whole variety of other impacts and therefore can be used to make estimates of impacts. Research on regrowth as an impact assessment tool may make possible some practical assessment until long-term research programs on monitoring nutrient budgets are developed, a process which could take decades.

Wildlife impacts

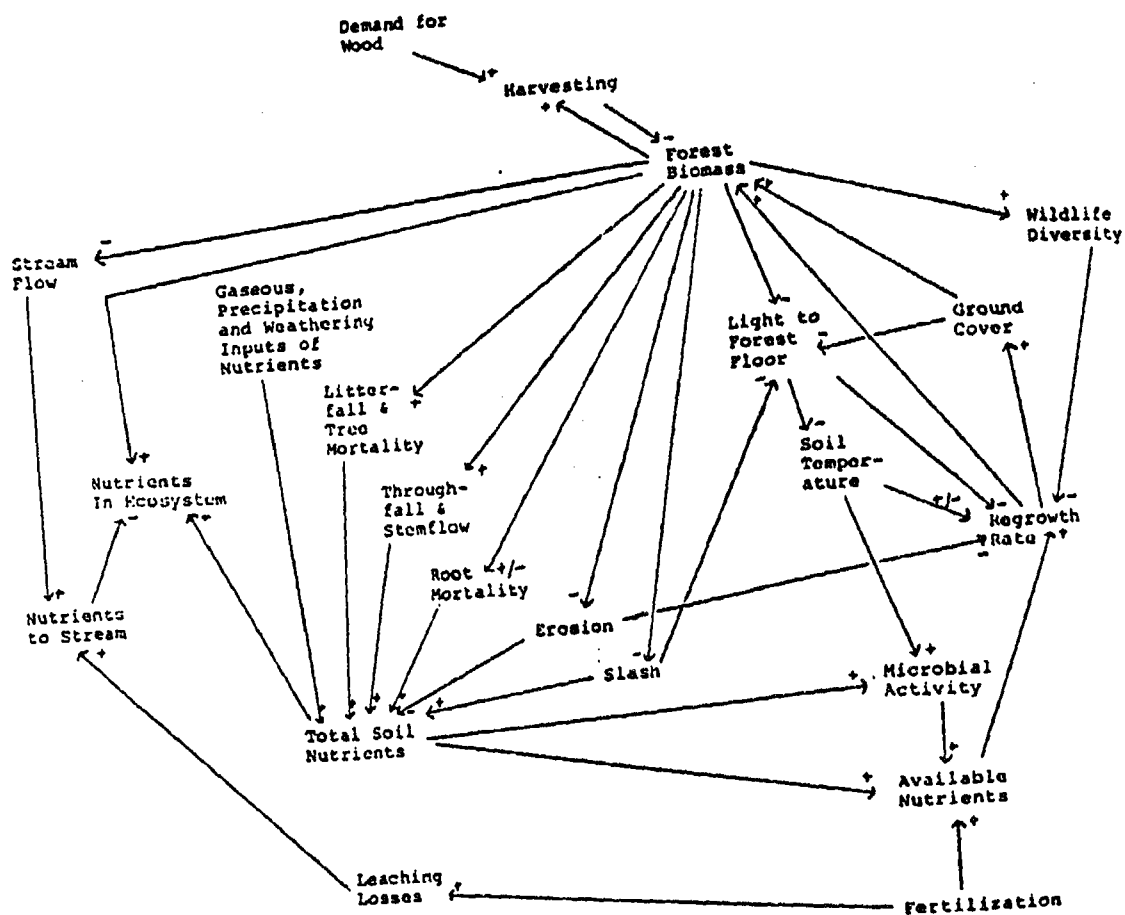
The effect of forest harvesting on wildlife has been the subject of several studies (Berner 1969, Conner and Adkisson 1975, Jordan 1967) and there is a general consensus that harvesting shifts species composition, frequently toward greater diversity. Although there may be temporary disturbance, most harvesting operations have little long-term effect on wildlife although the removal of late successional stands adversely impacts species dependent on them for survival. Certain game species such as grouse and deer may increase. Whole-tree chipping results in much less slash, which reduces cover for small animals, but in other respects it is generally similar to traditional harvesting methods. There is a need for further research on the effect of the size of clear-cut on species composition and on the benefits of preserving partially rotten trees as wildlife habitat.

Effect of harvesting techniques

Fuel wood harvesting will increase the tendency toward more intensive and more mechanized harvesting, the impacts of which involve the complex interaction within the forest ecosystem which are summarized in Figure 1.

Noncommercial wood harvesting might employ either whole-tree chipping or traditional logging techniques, and, depending upon silviculture and environmental factors, could involve clear-cutting, strip or patch cutting, or selection cutting. In most cases, the direction of the effect is clear but the magnitude is unknown. The magnitude of harvesting impacts is dependent upon the harvesting technique and the management of the operation (see Table 1). The general picture which emerges, however, is that, with the exception of nutrient budget impacts, whole-tree

FIGURE 1: Interactions Under the Influence of Harvesting



"+" = positive relationship, "-" = inverse relationship

Techniques on a Forest Ecosystem

Parameter	Effect	Whole Tree			Bole Only		
		Clear	Strip	Select	Clear	Strip	Select
Forest Biomass	-	vh	m	l	h	m	l
Stream Flow	+	h	l	l	h	l	l
Litterfall (1 year)	-	h	m	l	l	l	l
Root Exudates	-	h	m	l	h	m	l
Root Mortality	+	h	m	l	h	m	l
Throughfall, Stemflow	-	vh	m	l	h	l	vl
Soil Temperature	+	vh	m	l	m	l	vl
Ground Cover	-	h	m	l	m	l	l
Sapling & Tree Growth	-	h	m	l	h	m	l
Regrowth Rate	+/-	-h + m	+m	+m	+m	+m	+m
Wildlife Diversity	+/-	-h + m	+h	+m	-h + m	-m + m	+m
Total Soil Nutrients	-	vh	m	l	m	l	l
Nutrients to Stream	+	h	m	l	m	l	l
Leaching Losses	+	h	m	l	m	l	l
Available Nutrients	+	h	m	l	vh	h	m
Microbial Activity	+	h	m	l	vh	h	m
Erosion	+	h	m	l	l	l	l
Slash	+	l	l	vl	h	m	l
Nutrients in Ecosystem	-	vh	m	l	m	l	vl

"+"= increase following the harvest
 "-"= decrease following the harvest
 "h"= high; "m"= moderate; "l"= low;
 "v"= very

impact than clear cutting.

Socio-economic impacts

The development of a market for wood energy will provide additional jobs and income and generate state revenues. Table 2 gives an example: a summary of the direct and indirect employment generated by harvesting wood for a 50-megawatt wood-fired power plant in Vermont. A Bureau of Economic Analysis regional economic model for the state of Vermont predicts that this employment would produce 3.4 million dollars of income and 5.9 million dollars in indirect income (VanderWerf 1978).

TABLE 2: ESTIMATED EMPLOYMENT GENERATED BY HARVESTING
800,000 TONS OF GREEN WOOD ANNUALLY¹

	Direct Employment	Indirect Employment
Harvesting	117	64
Transportation	<u>37</u>	<u>18</u>
Total	154	82

¹Adapted from VanderWerf, 1978

The effects of harvesting wood for energy on other uses of forest fiber are uncertain. The impacts will depend on the silvicultural systems employed, and on the relative values of forest fiber used to produce materials and energy.

The development of a wood-energy market could provide opportunities for better forest management that could benefit both the forest products industry and the producers of wood energy.

However, the introduction of whole-tree chipping may lead to changes in the timber-harvesting industry, which in turn may affect the forest products industry and the forests themselves. The forest products industry is the mainstay of many rural economies and is continuing to expand (USFS 1974). Analyses of the effects of the wood energy market on this sector of the economy have not been undertaken. Similarly, there are no well-integrated assessments of forest use that can be used to predict the actual amounts of wood resources available for the production of wood-energy. Therefore the long-term socio-economic effects of harvesting wood for energy cannot be foreseen.

chipping of fuel wood results in minimal slash and therefore may be relatively acceptable when conducted in small strip, patch, or selection operations. Energy plantations, on the other hand, require close spacing of trees and frequent harvesting, which does not provide an attractive recreational environment. The main problems that need to be researched are those concerned with public policy to minimize aesthetic impacts and to achieve multiple use objectives.

Wood Transportation

Studies by Adler et al. (1978) have indicated that in most instances truck transportation is the most economic mode of transportation for harvested wood chips. Mill residues may in certain circumstances be economically transported by rail although the capital cost of loading and unloading facilities is high. Approximately 105 semitrailer van loads of wood chips per day would be needed to fuel a 50-megawatt wood-fired power plant. The environmental impacts of these trucks would include traffic congestion, noise, air pollution, and highway deterioration. These impacts are site-specific and studies in Vermont (High 1978) indicate that these may affect the choice of site for a plant in some cases. Highway deterioration, while locally important, is usually more than offset by the increased revenues from state taxes (Adler et al. 1978). One side-effect of improving woods roads to accommodate large semitrailers is to increase the accessibility for recreationists, with attendant benefits and costs.

Conversion Plant Construction

The environmental impacts of the construction of a wood-fired boiler for steam or electric power generation are generally similar to those of other comparable power plant projects. Construction over a period of about two years increases the work force, and causes local strain on housing, community, and commercial services, as well as noise, traffic, and localized air pollution impacts. Wood-fired power plants require rather larger areas for fuel storage than oil or coal plants, and they are likely to be built in rural areas or small towns where some of the socio-economic impacts may be more noticeable. However, wood-fired power plants are small in comparison with modern fossil fuel or nuclear power plants and the construction impacts are correspondingly smaller.

major types of environmental impacts: air pollution, ash disposal, and water pollution, and, in addition, some minor socioeconomic effects.

Air pollution

Wood combustion produces a range of emissions, the more important of which are shown in Table 3. It can be seen that the particulate emissions are the highest and that they vary with the proportion of bark burned as well as with the boiler's combustion characteristics. Fortunately control equipment is available to bring particulate emissions down to New Source Performance Standards where applicable (Boubel 1977, EPA 1973).

Sulfur dioxide emissions are much lower than from oil or coal; in this respect, wood has substantial advantages as a fuel in areas with sulfur dioxide pollution problems. There is still considerable doubt as to which emission factors are appropriate for carbon monoxide, hydrocarbons and nitrogen oxides as indicated by the range given in Table 3. More data on the emissions of these pollutants under a wide range of conditions is clearly needed. Theoretically, it is probable that these pollutants could be kept to the lower end of the ranges given or even below these levels by use of appropriate controls on combustion conditions.

In comparison with coal or oil, toxic heavy metals emissions are negligible. There is, however, a lack of data on the composition of the hydrocarbon emissions. During periods of poor combustion, there is a possibility that potentially hazardous organic compounds could be emitted.

Ash disposal

The amount of ash produced in the combustion of wood is variable and depends upon species and harvesting conditions. The ash content of bark is generally higher because of the soil collected during harvesting. Table 4 gives analyses of wood and ash. A 50-megawatt wood-fired power plant would produce forty to eighty tons of ash a day which would almost certainly be disposed of in landfills, although there could be a market for some ash as a soil conditioner and fertilizer. Apart from the lack of nitrogen, ash could provide a valuable source of plant nutrients and act as a lime substitute. Wood ash is low in heavy metals, is not considered toxic, and should not create a water quality problem if disposed of in properly designed landfills.

Water quality

Wood-fired boilers and power plants have similar water requirements to comparable fossil fueled boilers. Thermal pollution depends upon the choice of cooling system and is relatively independent of the fuel used. The only important

TABLE 3: ESTIMATED EMISSIONS FROM A
50-MW WOOD-FIRED POWER PLANT

<u>Particulates</u> ¹	<u>lbs/ton of fuel burned</u>	<u>tons/day</u>	<u>tons/year</u>
Wood: uncontrolled	10.0	11.27	4,000
controlled 99.8% ²	0.02	0.02	7
Wood & bark: uncontrolled	30.0	33.8	12,000
controlled 99.8%	0.06	0.068	24
Bark: uncontrolled	50.0	56.35	20,000
controlled 99.8% ²	0.10	0.113	40
 <u>SO₂</u> ¹	 1.50	 1.69	 600
 <u>CO</u> ¹	 2.0 to 60.0	 2.25 to 68.0	 781 to 24,000
 <u>NO₂</u> ¹	 10.0	 11.27	 3,990
 <u>Hydrocarbons</u> ¹	 2.0 to 70.0	 2.25 to 79.0	 781 to 28,000

Source: High 1978

1. From EPA 1976

2. Calculated based on EPA (1976) figures assuming use of multiple cyclones at 93.8% efficiency, followed by electrostatic precipitators at 97% efficiency.

TABLE 3: ANALYSES OF SOME SELECTED WOOD RESIDUE BURNED AS FUEL

Item	Jack pine	Birch	Maple	Western hemlock
Proximate analysis, percent				
Ash	2.1	2.0	4.3	2.5
Volatile	74.3	78.5	76.1	72.0
Fixed carbon	23.6	19.2	19.6	25.5
Ultimate analysis, percent				
Carbon	53.4	57.4	50.4	53.6
Hydrogen	5.9	6.7	5.9	5.8
Sulfur	0	0	0	0
Nitrogen	0.1	0.3	0.5	0.2
Ash	2.0	1.8	4.1	2.5
Oxygen (by difference)	38.6	33.8	39.1	37.9
Heat value, Btu/lb (bone dry)	8930	8870	8190	8885
Ash analysis, ppm				
SiO ₂	16.0	3.0	9.9	10.0
Al ₂ O ₃	6.3	0	3.8	2.1
Fe ₂ O ₃	5.0	2.9	1.7	1.3
CaO	51.6	58.2	55.5	53.6
CaCO ₃	4.9	13.0	1.4	9.7
MgO	5.5	4.2	19.4	13.1
MnO	1.6	4.6	1.0	1.2
P ₂ O ₅	2.8	2.9	1.1	2.1
K ₂ O	4.1	6.6	5.8	4.6
Mn ₂ O	3.1	1.3	2.2	1.1
TiO ₂	0.2	Trace	Trace	Trace
SO ₃	2.6	3.2	1.4	1.4
Fusion point of ash, F				
Initial	2450	2710	2650	2760
Softening	2750	2720	2820	2770
Fluid	2760	2730	2830	2780
Weight, lb/ft ³ (bone dry)	29	37-44	31-42	26-29

^a Average moisture of about 50 percent as received at firing equipment. Adapted from information compiled by the Steam Power Committee of the Canadian Pulp and Paper Association.

Source: Boubel 1977.

able components in the ash. This leads to a high base concentration and an alkaline water effluent. Compared to coal- or oil-fired boilers, the water effluent is relatively free of more toxic sulfur and heavy metal components.

CONCLUSION

The major impacts of the use of wood for energy are associated with harvesting impacts on soil nutrients, the productivity of the forest, and the competing uses for the forest resource base. Locally, air pollution impacts of operation may be significant. Environmental impacts can be minimized by careful management and control and are likely to prevent increased use of wood for energy, at least in the short term.

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Performance Criteria (IPC) [12, 13] prepared by the National Bureau of Standards (NBS) address many health and safety considerations that need to be considered by system designers. For example, factors such as the flammability and toxicity of heat transfer fluids are often not considered in the design of systems. These problems are compounded by the lack of clear guidelines as to which fluids constitute hazards that warrant special consideration.

This report is intended to create an increased sense of awareness of the health and safety aspects of solar heating and cooling applications by extracting and amalgamating pertinent provisions of the MPS and IPC documents. Additional discussion of their rationale and other considerations are presented. Emphasis is placed on the safety provisions in the MPS document which are consistent with those in the commercial IPC document. The provisions in these two documents which were prepared in November 1976 and March 1977 represent an update of the provisions in the residential IPC document which was prepared in January 1975. The provisions in the MPS document are somewhat more prescriptive than those in the performance based IPC document. Safety related issues related to both active and passive solar energy systems are addressed by both documents.

In applying the MPS and IPC standards, recognition must be given to the type of project under consideration; single family, multi-family, institutional or commercial. Though very few of the requirements note any difference in treatment for a specific hazard (for example, a safe potable water system is considered essential in any type of occupancy) they often include standards by reference that do embody significantly different treatment for different types of buildings. For example, fire resistance requirements vary with different occupancies and solar components which form part of a fire resistant building element must be able to meet these various requirements.

Some of the areas that are discussed include: structural safety, heat transfer fluid toxicity and flammability considerations including the protection of potable water, effects of solar equipment on the fire resistance of buildings, mechanical system protection, and protection from physical hazards.

2. GENERAL PROVISIONS

The overall philosophy of the MPS and IPC documents with regard to safety is to prevent the creation of a hazard, due to the presence of solar equipment, which is greater than that which would be found in a non-solar building.

The incorporation of solar systems into the living unit shall not create an environment which is more hazardous to the occupants than that of a conventional living unit. Materials and the construction used in installation of solar systems shall be in accordance with the fire protection provisions of S-405.

(S-600-6.1)**

In keeping with this philosophy, frequent reference is made throughout these documents to nationally recognized codes and standards.

Except as modified herein, materials, equipment and installation shall be in accordance with the standards and nationally recognized model codes cited within the body of this document, the current applicable editions and titles of referenced standards and codes are contained in Appendix E. State and local codes which deviate from nationally recognized codes or standards in order

*Numbers in brackets [] indicate references given at the end of this report.

**Indented paragraphs are taken from the MPS [1]; designations in parenthesis () are references to specific MPS sections. References in MPS paragraphs are given as footnotes in this report.

These provisions include considerations such as the flammability of materials used in solar equipment, the influence of solar installations on the fire resistance of the building and the provision of space for access and emergency egress in the event of a fire.

3.1 FLAMMABLE MATERIALS

These provisions are primarily concerned with heat transfer fluids and insulation materials. The remainder of the materials used in solar installations are similar to those used in conventional installations and are covered by reference to nationally recognized codes.

Assemblies and materials used in the solar systems shall comply with the nationally recognized codes for fire safety under all anticipated operating and no flow conditions.

(S-515-1.1)

The storage, piping and handling of combustible liquids shall be in accordance with the Flammable and Combustible Liquids Code NFPA No. 30.

(S-600-6.2)

3.1.1 Heat Transfer Fluids

Some of the heat transfer fluids that are used in solar installations are combustible and/or toxic. A number of installations have used a fluid having a flash point of about 140°F under conditions where the fluid could be heated under normal operating conditions to about 200°F and, under "no flow" (stagnation) conditions, to temperatures of 350°F or higher.

The solar MPS has several provisions related to the flammability of heat transfer fluids.

Detailed labeling requirements are specified to identify potential hazards.

The provisions of the Federal Hazardous Substances Act (1971) shall apply to heat transfer fluids. In addition, heat transfer media classified as combustible shall be labeled as such.

Emergency first aid instructions shall be included on the label of toxic heat transfer fluid containers. A technical data sheet shall be provided with all heat transfer fluids which contains the following information.

Service temperature range
Viscosity over service temperature range
Freezing point
Boiling point
Flash point
Auto ignition temperature
Specific heat
Vapor pressure over service temperature range
Instructions for inspection, treatment and disposal of fluid
Emergency first aid instructions.

For toxic fluids, a list of the chemical components of the fluid shall be available expressed in mg./liter. This list shall include any substances which comprise more than 0.10% of the medium.

(S-515-8.1.1)

Requirements are placed on systems using combustible liquids. The system must be designed to eliminate the hazard and limitations are placed on the flash point of such fluids.

Heat transfer fluids which require special handling (e.g., toxic, combustible, corrosive, explosive, etc.) shall not be used unless the systems in which they are used are designed to avoid unnecessary or unreasonable hazards; see Section S-615-10.1.

(S-515-8.2.1)

Temperatures attained by fluids in solar systems under operating and no flow conditions shall not exceed a temperature which is 100 F below the flash point of the fluid. In no case shall a liquid with a flash point below 100 F or a flammable gas be used. Flash point shall be determined by the methods described in NFPA No. 321, Basic Classification of Flammable and Combustible Liquids.

Commentary: NFPA No. 321 (1973) defines Flammable Liquids as those with flash points below 100 F and Combustible Liquids as those with flash points at or above 100 F. This section prohibits the use of flammable liquids (flash point below 100 F) and permits the use of combustible liquids (flash point at or above 100 F) under prescribed conditions. In common, non-technical usage, the term flammable liquid frequently refers to any liquid with a flash point, including liquids classified as combustible.

(S-515-8.2.2)

It is anticipated that the flash point requirement may be changed by the Department of Housing and Urban Development (HUD) to the less stringent provision given below recognizing the differing levels of hazard presented by different types of installations. However, before such changes to the MPS can be made, HUD procedures require public review and comment.

Proposed Revision*

"The Flash Point of a liquid** heat transfer fluid shall equal or exceed each of the following temperatures:

- A. 100 F;
- B. 50 F above the maximum design operating temperature of the solar system;
- C.
 - 1) 200 F below the maximum stagnation temperature attained by the collector during the test required by Section S-515-2.1.2, provided that the collector manifold assembly is located outside the building and exposed to the weather;
 - 2) the maximum stagnation temperature, as defined above, in all other manifold configurations."

The rationale for the different values in item C is that a system leak under no-flow conditions is most likely to occur in the collector or in the collector manifold assembly. A lower flash point liquid will be acceptable when the manifold assembly is external to the building, since there is a significant lower hazard of ignition under such conditions. Where a leak could occur in an enclosed area which might have an ignition source (attic-located heater, fan, or other electrical device, for instance), there is a higher hazard justifying a higher safety standard.

Provisions are also specified in the solar MPS for the detection of toxic and/or combustible fluids and for the identification of points from which such fluids can be discharged.

* Memorandum to Solar Transfer Fluid Manufacturers from David C. Moore, HUD, December 19, 1977.

**A "liquid heat transfer fluid" is defined as the operating fluid including water or other liquid base and all additives at the concentration used under operating conditions.

distinguish them clearly. Furthermore, if any such materials are to be stored on the premises, they should be stored in containers which are labeled in accordance with the Federal Hazardous Substances Act and be protected from easy opening by children e.g., childproof lids. Safe storage locations should be provided.

(S-615-8.1.2)

Drains and other designated fluid discharge or fill points in solar systems at which toxic, combustible, high temperature or high pressure fluids may be discharged shall be labeled with a warning describing the identification and hazardous properties of the fluid, instructions concerning the safe handling of the fluid, and emergency first aid procedures.

Commentary: The original fluid containers will frequently be discarded after the system is charged which could result in no record of the fluid's properties being retained. The system drain is the point at which the owner or service personnel are most likely to contact the heat transfer fluid and permanent labeling should be retained at that point. Identification may be provided by attaching a tag containing the required information such as may be supplied by the heat transfer fluid manufacturer.

(S-615-8.1.3)

Another important provision is concerned with the warning of maintenance personnel about hazards that can occur during system maintenance. A number of fires have occurred as a result of workmen trying to repair leaks with a soldering torch. In automobile fuel systems, one automatically expects gasoline to be present; however, in solar equipment the heat transfer fluids present an unfamiliar hazard.

The manual shall completely describe the H and/or DHW systems, their breakdown into subsystems, their relationship to external systems and elements, their performance characteristics and their required parts and procedures for meeting specified capabilities.

The manual shall list all parts of the systems, by subsystem, describing as necessary for clear understanding of operation, maintenance, repair and replacement; such characteristics as shapes, dimensions, materials, weights, functions, and performance characteristics. The manual shall include a tabulation of those specific performance requirements which are dependent upon specific maintenance procedures. The maintenance procedures including ordinary, preventive and minor repairs, shall be crossreferenced for all subsystems and organized into a maintenance cycle. The manual shall fully describe operating procedures for all parts of the system including those required for implementation of specified planned changes in mode of operation. The instructions shall provide warning against hazards that could arise in the maintenance of the system and shall fully describe precautions that shall be taken to avoid these hazards.

(S-600-3.2)

The disposal and containment of toxic and/or flammable fluids are discussed on pages 11 and 12 of this report.

These requirements apply to both fixed and movable insulation installed in conjunction with or as an integral part of the solar system. Materials used for insulation shall be of sufficient proven effectiveness and durability under the expected operating conditions to assure that required design conditions concerning heat losses, sound control and fire rating are attained. Insulation in contact with the ground shall not be adversely affected by soil, vermin or water. Insulating materials shall be in accordance with 507-3 of the MPS and S-607-3. Insulating materials for air ducts shall be in accordance with Section 507-1 of the MPS. Materials used for vapor barriers shall be in accordance with Section 507-2 of the MPS.

Commentary: When movable insulation is used in passive systems, design consideration should be given to ensure protection of the insulation from structural damage, degradation due to weather or other degrading factors.

(S-515-11.1)

The flame spread classification index for all insulation materials shall not exceed the following values:

Plastic Foam	25
Loose Fill Insulation	50
Other Insulation Material	150

The ASTM E 84 flame spread test method shall be the basis for evaluating the surface burning characteristics of the insulation materials. Where fibrous blankets with facings are to be used, the surface burning characteristics of the complete faced insulation blanket shall be measured.

*Commentary: No single test is sufficient to provide a full estimate of performance of a product in a fire. Plastic foams and loose fill insulation are difficult to evaluate in ASTM E 84. The requirement of flame spread classification of 25 maximum for plastic foams and 50 for loose fill insulation will provide as much safety assurance as is possible with current test methods. Such a classification shall not be construed as the equivalent of "noncombustible." Many insulation materials, including those consisting of cellulose, plastic foam and fibrous glass (containing organic binder) are combustible materials which will burn and release heat, especially when exposed to continuous large fire sources.**

(S-515-11.1.1)

Chemical retardant insulations shall retain their flame resistance throughout their service lifetime. The procedures and equipment specified in ASTM C739-73, Section 10.4, "Flame Resistance Permanency," shall be used in judging the effect of aging on the permanence of any flame retardants used during manufacture.

(S-515-11.1.2)

Materials used for thermal insulation shall be in accordance with S-515-11 and may be applied to the following areas: walls, roofs, ceilings, floors, pipes, ducts, vessels, and equipment exposed to the external environment.

Exposed plastic foam (untreated or fire-retardant treated), Kraft-asphaltic vapor barrier on mineral and organic fiber insulations, and non-fire-retardant treated

*A Consumer Product Safety Commission regulation for cellulose insulation becomes effective on September 8, 1978. Modifications, including institution of radiant panel testing, are currently under consideration.

by ASTM E 119. Thermal barriers shall be installed in a manner such that they will remain in place for a minimum of 15 minutes under the same test conditions.

Installed insulation and vapor barriers shall not make contact with recessed light fixtures, motors, fans, blowers, heaters, flues and chimneys. Thermal insulation shall not be installed within 24 inches of the top or within 3 inches of the side of a recessed electrical fixture enclosure, wiring compartment or ballast unless labeled for the purpose. To retain loose fill insulation from making contact with other energy-dissipating objects, a minimum of 2 inches of air space should be provided and assured by the use of blocking.

Commentary: Although a degree of material combustibility is allowed, the intent is to allow insulating materials which are not more combustible (or flammable) than existing construction and insulation materials, and to preclude any increased fire hazard due to the retention of heat from energy dissipating objects. In areas where occupants are likely to be engaged in normal activities, the insulation should perform its intended function without the increased risk of ignition, rapid flame spread and heat and smoke generation. Insulation in concealed spaces may be a particular fire problem due to its susceptibility to smoldering and its inaccessibility for fire fighting.

(S-607-3.1)

An important consideration is that insulation used inside air collectors may give off harmful substances that can enter a building's air duct system. The selection of materials which comply with existent standards for air handling systems should prevent a hazard from occurring by this means.

Design of all warm air heating systems shall be in accordance with the recommendations of the ASHRAE Guide or applicable manuals of NESCA, SMACNA, and ARI. Installation shall comply with NFPA Standards 31 and 54 and either NFPA 90A or 90B, as applicable.

(S-515-3.3)

A number of air collector designs utilize types of plastic foam materials that are not capable of meeting these standards.

3.2 FIRE RESISTANCE OF BUILDING ASSEMBLIES

Safety concerns include the effects that the presence of solar components will have on the fire resistance of building assemblies. Passive solar energy systems may utilize large expanses of glazing which may be flammable, or may employ large air plenums throughout the building. Such configurations need to be considered in addition to those used in the more conventional active systems.

The incorporation of solar subsystems shall not reduce the fire resistance ratings required by 405.4 of the MPS.

Commentary: Roof-mounted collectors which are an integral part of the roof construction shall not reduce fire resistance rating of the roof assembly.

(S-405-4.1)

Penetrations through fire-rated assemblies shall not reduce the fire-resistance ratings required by 405-4 of the MPS.

(S-405-4.2)

Major solar system components that are integral parts of assemblies which normally require firestopping shall be firestopped on all sides. Firestopping shall be wood blocking of minimum 2 inch nominal thickness or of noncombustible

in the case where a solar collector is an integral part of a wood framed wall which would normally be firestopped between studs, firestopping shall be required in the wall above and below the solar collector.

(S-405-7)

Installation of solar collectors or system components on or as an integral part of the roof shall not reduce the fire retardant characteristics of the roof covering below the level specified in 405-12 of the MPS.

(S-405-12)

The elevated temperatures that can arise in solar equipment can also create a hazard if adequate clearance is not provided.

Combustible solids adjacent to solar equipment or an integral part of a solar component shall not be exposed to elevated temperatures which may cause ignition.

Commentary: Heating of cellulosic materials as well as other combustible materials over an extended period of time may result in the material reaching and surpassing its autoignition temperature. The most commonly accepted ignition temperature of wood is 392 F. However, studies have indicated that wood may ignite when exposed to a temperature of 212 F for prolonged periods of time. The ignition temperature of plastics may be above or below those of cellulosic materials. Clearances for HVAC equipment, ducting and piping are discussed in NFPA No. 89N. When applicable, clearances specified by a nationally recognized testing laboratory may be used.

(S-600-6.4)

3.3 EMERGENCY ACCESS AND EGRESS

A final consideration with regard to fire safety is ease of access and the provision of adequate means for egress in the event of an emergency.

Components of the solar system shall not impinge on the requirements of Section 304-3 of the MPS.

Commentary: Reasonable outdoor open space must be maintained for livability, service, emergency access, isolation of fire and protection of adjacent property.

(S-304-2)

The design and installation of the solar heating and domestic hot water systems shall not impair the normal movement of occupants of the building or emergency personnel.

***COMMENTARY: SPECIAL CONSIDERATION SHOULD BE GIVEN TO THE EFFECT OF THE CONFIGURATION OF ROOF-MOUNTED COLLECTORS ON FIRE EXITING, FIRE FIGHTING OR EMERGENCY RESCUE.**

(S-402-1.1)

Components of the solar system shall not be located in such a way as to interfere with the primary means of occupant egress.

*Bold-faced type is used in the MPS to indicate provisions applicable to multi-family dwellings only.

Piping and equipment shall be located so as not to interfere with normal operation of windows, doors, or other exit openings and so as to prevent damage to piping, equipment, or injury to persons.

(S-615-10.12)

Although it is not anticipated that problems will arise in this area because of previous experience with building codes, it is an important consideration especially in retrofit situations where limited space is available.

4. PROTECTION OF AIR AND POTABLE WATER

Serious health hazards can occur in solar installations as a result of contamination of air or water. The potential for leakage of toxic heat transfer fluids in liquid systems is ever present where such liquids are used. In addition, mold, mildew, fungi, or chemicals given off from the materials used in solar components can cause health hazards in both air and liquid systems. We recently became aware of a health problem which may have been caused by the thermal decomposition of the materials in an air system and the subsequent entry of decomposition products into the building's air system. The following general provisions address these problems:

No material, form of construction, fixture, appurtenance or items of equipment shall be employed that will introduce toxic substances, impurities, bacteria or toxic chemicals into potable water and air circulation systems in quantities sufficient to cause disease or harmful physiological effects.

Commentary: This situation is of concern not only as it pertains to ducts, piping, filters and joints but also to storage areas, such as rock beds. In addition, the growth of fungus, mold and mildew is possible when collectors are applied to a roof surface over the water tight membrane. If the collectors are in contact with the membrane or held away from the membrane to allow for drainage, the shaded membrane area can support the growth of mildew and other fungus in some warm, moist climates. Special design consideration should be included to avoid this problem in climates where it can occur.

(S-501-3.1)

Components and materials used in the H and DHW systems shall not promote the growth of fungi, mold or mildew in accordance with applicable codes, the test specification of UL 181-74, Section 10 and MPS, Appendix D, Section E.

Commentary: Special consideration should be given to the presence of fungi in air handling systems since such micro-organisms are frequently allergenic.

(S-600-6.7)

Thermal storage tank materials, including any interior protective coatings and the heat storage medium used, shall not impart toxicity, undesirable tastes, or odors to either air or water intended for human consumption. For liquid systems, the requirements of the U.S. Public Health Service Drinking Water Standards shall apply.

(S-515-7.4.1)

cut-off points at which various degrees of protection must be taken. For example, a number of the toxicity tables list propylene glycol as slightly toxic. A substance with such a ranking most likely does not fit under the definition of potable; if it did no safety precautions need to be taken, yet it is not as hazardous as many other substances that are used in heat transfer fluids. This problem is compounded by factors such as: (1) the use of additives to modify fluid properties; (2) the possible formation of harmful decomposition products, e.g., by thermal degradation; (3) the fact that liquids are generally available in varying grades of chemical purity; (4) the possibility that the system will be refilled in the future with a hazardous liquid; and (5) the possibility that circulation in a closed loop system for prolonged periods of time will even result in the contamination of potable liquids, e.g., by metal ion buildup.

The MPS and IPC documents do not present standards to determine the degree of toxicity presented by various liquids. They are primarily concerned with the provision of adequate protection when potentially hazardous substances are used.

The provisions for the detection of toxic and/or combustible fluids (S-615-8.1.2) and for the identification of discharge points for such fluids (S-615-8.1.3) have already been presented in Section 3. Another important consideration is the heat exchange interface that may exist between a non-potable liquid and potable water.

When nonpotable liquid is used in a solar energy system to transfer heat to domestic (potable) hot water, the design of the heat exchanger shall be such that either a minimum of two walls or interfaces are maintained between the nonpotable liquid and the potable water supply or protection is provided in such a manner that equivalent safety is provided.

Commentary: Double wall heat exchanger designs are one way of meeting the intent of this criterion. When double wall heat exchanger designs consisting of two single wall heat exchangers in combination with an intermediary potable heat transfer liquid are used, leakage through one of the walls would result in a single wall configuration. Although this design is considered to meet the intent of this criterion, there are several other designs that avoid this problem.

The use of single wall configurations which solely rely upon potable water pressure to prevent contamination is not considered to be an acceptable solution. Similarly, extra thick single walls are not considered to meet the intent of this requirement.

For approval of other than double wall designs, the procedures described in S-101 should be utilized.

(S-515-9.1)

This problem is complicated by the lack of definitive standards as to what constitutes acceptable double wall or equivalent protection.

Other provisions relating to the handling of non-potable liquids are as follows. The second of these provisions parallels the previous requirement for heat exchangers.

Potable water supply shall be protected against contamination in accordance with the prevailing model plumbing code having jurisdiction in the area, as well as the requirements which follow.

(S-615-10.1)

Circulation loops of subsystems utilizing nonpotable heat transfer fluids shall either be separated from the potable water system in such a manner minimum of two walls or interfaces is maintained between the nonpotable liquid and the potable water supply or otherwise protected in such a manner that equivalent safety is provided.

Commentary: Double wall heat exchanger designs are one way of meeting the intent of this criterion. When double wall heat exchanger designs consisting of two single wall heat exchangers in combination with an intermediary potable heat transfer liquid are used, leakage through one of the walls would result in

pressure to prevent contamination is not considered to be an acceptable solution. Similarly, extra thick single walls are not considered to meet the intent of this criterion.

For approval of other than double wall designs, the procedures described in S-101 should be utilized.

(S-615-10.1.1)

In buildings where dual fluid systems, one potable water and the other non-potable fluid, are installed each system may be identified either by color marking or metal tags as required in ANSI A13.1-1956 [1] or other appropriate method as may be approved by the local administrative code authority. Such identification may not be required in all cases.

(S-615-10.1.2)

Backflow of non-potable heat transfer fluids into the potable water system shall be prevented in a manner approved by the local administrative code authority.

Commentary: The use of air gaps and/or mechanical backflow preventers are two possible solutions to this problem. The following are some recognized standards that may be acceptable to the local administrative code authority: Complete titles are given in Appendix E.

Air gaps	- ANSI-A112.1.2
Backflow preventers	- FCCCHR Chapter 10
	IAPMO PS 31-74
	AWWA C506-89
	A.S.S.E. 2011
	A.S.S.E. 1012
	A.S.S.E. 1013
	A.S.S.E. 1015
	A.S.S.E. 1020
	ANSI-A112.1.1

(S-615-10.1.3)

The design and installation of the solar system, its subsystems and components shall be accomplished in such a manner as to provide complete protection of the potable water supply. Such installations shall be in accordance with Chapter 10 of the National Standard Plumbing Code and other applicable codes (see Section S-615-10).

(S-600-6.9)

Protective measures that should be taken when potable make-up water is added to tanks containing non-potable water are addressed in the following provision:

Tanks of large capacity should have an indicator or other means for determining that the tank is full. Tanks shall have overflows with outlets located so that spillage will not run into the building structure or damage the premises. Tanks that do not contain potable water but require make-up water from the potable water system shall be filled by way of an air gap or other means acceptable to the administrative authority having jurisdiction.

(S-615-7.5)

4.2 PROTECTION OF AIR QUALITY

Provisions for the protection of air quality from mold, mildew and fungi (S-600-6.7) and for protection from contamination of air by system components (S-501-3.1) have already been presented in Section 4. The importance of these provisions cannot be overemphasized, especially with regard to the possibility of having mold and fungi in rock bed storage and the possibility of using materials in air collectors that decompose at "no flow" (stagnation) temperatures and give off harmful substances that subsequently get into building air handling systems. This latter phenomenon, outgassing, is thus not only a problem when condensates build up on cover plates but also when potentially harmful substances are given off.

[1] Scheme for the Identification of Piping Systems, ANSI A13.1-1956.

the outlet side of rockbed storage in active systems.

Commentary: The gravel used for rock bed storage with air systems is selected for size and freedom from dirt and dust. Therefore, smooth and washed material combined with the use of filtered air is desirable to provide a maintenance free, clean distribution system. Fan grilles should be removable or hinged to permit access to the fan and motor for cleaning, servicing, replacement or repair.

(S-615-13.2)

The concentration of the vapor of the heat transfer medium in the building's interior atmospheric environment shall not exceed 1/10th the threshold limit value (TLV) for that particular medium in an 8-hour period.

Commentary: The TLV is primarily concerned with industrial exposure. Because routine household exposure could be for much longer time periods, the 1/10th value of the TLV is recommended. TLV's are under continuous review; a list of currently adopted values is published by the American Conference of Government Industrial Hygienists.

(S-515-8.2.3)

5. COLLECTION AND DISPOSAL OF HAZARDOUS FLUIDS

Adequate consideration is seldom given to the safe disposal of hazardous heat transfer liquids. The general rule of thumb appears to be that leakage and liquids released from pressure relief valves should be allowed to go where they may. In addition to being hazardous, many of these liquids can cause severe deterioration of building materials, e.g., roofing materials. Consideration is given in the MPS and IPC documents to the intentional disposal of such hazardous liquids as well as the catchment and disposal of liquids inadvertently released from the system. The temperature of the fluids being released also needs to be considered.

Leakage from assemblies or subassemblies which contain heat transfer fluids shall not significantly impair the function of other components which may come in contact with the leaking heat transfer fluid or create a safety hazard.

(S-515-1.10)

Systems utilizing other than air or potable water as a heat transfer fluid shall provide for the catchment and/or harmless removal of these fluids from vents, drains or re-charge points as approved by local administrative code authority. Potable water shall be discharged to suitable drainage systems connected to the building or site drains. See MPS Section 615-9.

(S-615-9.1)

Adequately sized and protected receptacles shall be provided when toxic and/or combustible fluids are used in order to collect and store the overflow from: pressure relief valves, liquids drained from the system when it is being serviced, and identifiable leakage. Provisions of MPS Section 615-4.4 (Section 615-4.5 in MPS 4920.1) shall be applied.

Commentary: When a toxic heat transfer fluid is used (see Section S-515-8.2), a catch basin must be provided. It must be sufficiently large to accept dilution as required by MPS Section 615-9 before disposal.

If the diluted medium is biodegradable through conventional sewage treatment, the diluted medium is to be flushed into the sanitary sewer system (not the storm sewage system). Consideration should be given to the effect of flushing solar systems on the "Basic Design Loading" for sewage treatment, Section CS 603, HUD Handbook 4940.3, "Minimum Design Standards for Community Sewage Systems."

(S-615-9.2)

Fluid Disposal - Biodegradability and Aquatic Quality

- a. A list of the chemical components of the heat transfer medium must be provided in mg/liter. This list must include any substances which comprise more than 0.10% of the medium.
- b. The organic constituents of these substances must have a five-day Biochemical Oxygen Demand (BOD), using sewage seed, of at least 70% of the theoretical oxygen demand. This test shall be in conformance with the Standard Methods for the Examination of Water and Waste Water, American Public Health Association (1971).
- c. The concentration of chemical constituents must be compared with the 96 Hour LC-50* bioassay value for protection of aquatic life. This comparison is to be made in accordance with the Water Quality Criteria 1972.

Using the gallon/day capacity of the local sewage treatment plant, approximate the concentration at the treatment plant. If the dilution of the chemical constituents is 1/10th the LC-50 value or greater at the sewage treatment plant, the heat transfer medium must be diluted before emptying into a public sewer.

Commentary: Means for the disposal of heat transfer fluids are discussed in Section S-815-9 of this document. Consideration should also be given to the effect of flushing solar systems on the "Basic Design Loading" for sewage treatment, Section CS 803, HUD Handbook 4940.3, Minimum Design Standards for Community Sewage Systems. A preliminary draft of the Environmental Protection Agency's Quality Criteria for Water, October 10, 1975, is currently under review. After its publication in the Federal Register, EPA's criteria will supersede those currently listed

(S-515.8.2.4)[4]

6. TEMPERATURE AND PRESSURE PROTECTION

There are a number of provisions in the MPS and IPC documents concerned with the provision of adequate temperature and pressure relief. Additional provisions are concerned with the testing of systems at pressures greater than those anticipated in actual service, and with the labeling of components as to allowable operating conditions (e.g., maximum and minimum allowable operating temperatures and pressures). Another provision is concerned with the protection of collectors that are not designed to withstand cold filling while at stagnation temperatures. This has been known to result in potentially hazardous failures in at least one design of evacuated tube collector. The following provisions for the temperature, pressure, and vacuum protection of various solar hardware elements are given in the solar MPS.

The control subsystem shall be designed so that in the event of a power failure, or a failure of any of the components in the subsystem, the temperatures and/or pressures developed in the H and DHW systems will not be damaging to any of the components of the systems and the building or present a danger to the occupants. The safety devices shall meet the requirements of Section 515-6.4

*LC = Lethal Concentration.

in those parts of the energy transport subsystem containing pressurized fluids. A pressure release device shall be provided in each portion of the system where excessive pressures can develop. Each section of the system shall have a pressure relief device so that no section can be valved off or otherwise isolated from a relief device. Automatic pressure relief devices shall be set to open at not more than the maximum pressure for which the subsystem is designed.

Relief devices shall drain to locations in accordance with Section S-615-9.1.

Commentary: Care should be taken in the design and layout of the fluid transport system to prevent conditions in which locally excessive pressures are developed as a result of flow restrictions. Precautions must be taken to assure that heat transfer liquids do not discharge on asphalt base roofing materials or other types of roofing or locations which may be hazardous, cause structural damage, building finish discoloration, or damage to plant materials. (S-615-14.1.1)

The importance of taking into account the effects of flow restrictions on pressure relief can't be overemphasized. Air locks can result in catastrophic failures.

Those portions of heating systems which contain liquid heat transfer fluids and are not directly connected to the potable water supply shall not leak when pressures of not less than 1-1/2 times their design pressure are imposed for a minimum of 15 minutes [1]. The pressure shall be gradually applied and sustained for a sufficient length of time to permit examination of all pipe joints for leakage. Those portions of the system using domestic hot water shall not leak when tested in accordance with the code having jurisdiction in the area where the system is used. In areas having no building code, a nationally recognized model code shall be used [1].

(S-615-10.10.1)

Collectors shall be labeled to show the manufacturer's name and address, model number, serial number, and collector weight (dry). Technical data sheets shall also be provided which include collector efficiency as measured according to S-615-2.2, maximum allowable operating and no-flow temperatures and pressures, minimum allowable temperatures, and the types of fluids which can and cannot be used.

Commentary: Other data related to the installation and operating conditions or characteristics is desirable such as the pressure drop across the collector.

(S-515-2.1.1)

The solar energy system, including collectors, pipes, tanks, and heat exchangers shall be protected against possible collapse by design or by provision of vacuum relief valves.

Commentary: System components may be subjected to collapse if heating system leakage were to occur or if the system were drained without venting.

(S-615-14.1.2)

Automatic flow control valves shall be provided for collectors unable to withstand temperature shock.

(S-615-14.1.3)

[1] "The BOCA Basic Plumbing Code," "Southern Standard Plumbing Code," "The Uniform Plumbing Code," and "The National Plumbing Code."

Also, so that solar installations do not adversely effect the conventional heating and hot water system and vice versa, provisions are included for safe interconnection.

The interconnections of the auxiliary energy system to the solar energy system shall be made in a manner which will not result in excessive temperature or pressure in the auxiliary system or in bypassing of safety devices of the auxiliary system.

(S-615-11.2)

7. STRUCTURAL SAFETY

The MPS and IPC documents address the various types of structural loads that can be imposed on solar hardware. In addition to the loads that would normally be expected on a building, consideration must be given to the possibility of wind uplift loads on collectors mounted at an angle to or parallel to roofs. Other important considerations are the weakening of structural members by penetrations, especially in retrofit situations and the possibility of cover plates falling off collectors and unusual snow loads caused by solar component configurations. Where structural analysis cannot be performed, testing may be required.

GENERAL

This section contains those supplemental requirements to Chapter 6 of the MPS needed to cover solar systems which utilize conventional structural materials (materials covered by the current MPS edition). Unless specifically modified herein, the requirements of MPS Chapter 6, apply in addition to the supplemental requirements in this section.

All structural design for solar systems and their mounting structures shall be based on generally accepted engineering practice. All loading shall be in accordance with ANSI A58.1 except as shown otherwise in this document or MPS.

(S-601-1)

DESIGN DEAD LOADS

In calculating the dead loads for solar systems, the weights of the transfer liquid in the collector, liquid in storage tank, and liquid in other subsystems and components shall be included, except when using dead load to resist uplift or overturning.

Commentary: Liquids are normally present in systems in which they are the heat transfer medium and thus are a long term sustained load where creep is a consideration. They also effect seismic forces in a fashion similar to any other dead load. However, it is possible to remove liquid, thus they should not be counted on to resist uplift.

(S-601-2)

DESIGN LIVE LOADS

Roof Mounted Solar Systems

Resistance to design live roof loads prescribed in Table 6-1.2 of MPS 4900.1 (Table 6-1.3 of MPS 4910.1 and 4920.1) shall not be required for collector panels that are mounted on roofs but do not form an integral part of the roof

The roof will need to be repaired from time to time; therefore, it must support the workmen making the repairs, regardless of the wind and snow loading requirements. This is not the case for accessible roof-mounted collectors; they do not need to support workmen when being repaired. Hence, they need only sustain the required environmental loading (wind, snow and hail).

(S-601-3.1)

Maintenance Loads

All components of the solar energy systems which must support maintenance personnel shall resist a single concentrated load of 250 lbs. distributed over a 4 sq. in. area, acting on the installed component in the most critical locations. Special allowance shall also be made for heavy maintenance equipment, if used.

(S-601-3.2)

WIND LOADS

Flat Plate Collectors Mounted on Roofs and Walls

Wind loads on flat plate solar collectors shall be those specified for roofs and walls in Section 601-6 of the MPS or as modified in paragraphs S-601-4.1.1, .2, .3, and .4 below.

(S-601-4.1)

Flat plate collectors that are mounted with their cover plates and back surfaces flush with the surface of the roof shall resist the wind loads that would have been imposed on those areas of the roof covered by the collectors.

(S-601-4.1.1)

Flat plate collectors mounted at an angle or parallel to the surface of the roof on open racks shall resist any uplift load caused by the impingement of wind on the underside of the collector. This wind load is in addition to the equivalent roof area wind pressure and suction loads, and shall be determined by utilizing accepted engineering procedures which may include wind tunnel testing. Equivalent roof area wind loads are those wind loads that would have been applied to the areas of the roof occupied by the collectors. Equivalent roof area wind loads shall be applied to the outer cover plate of the collectors.

(S-601-4.1.2)

In calculating design wind loads for flat plate collectors mounted on roofs, the internal pressure coefficients, C_{pi} , listed in Table 11, ANSI A 58.1, shall be taken as zero for the wind pressure within a collector. Collectors that form an integral part of the roof structure shall resist the internal pressures from the inside of the building just as any other roof member.

(S-601-4.1.3)

Wind loads on flat plate collectors mounted at an angle to a vertical wall shall be the same as those required for equivalent roof eave area as stipulated in section 6.5.3.2.4 of ANSI 58.1. Wind loads on flat plate collectors mounted parallel to, or integral with vertical walls shall be the same as those required for exterior walls.

(S-601-4.1.4)

Other Types of Solar Collectors Mounted on Roofs and Walls

Wind loading on other types of solar collectors shall be determined using the results of accepted engineering procedures including the MPS and ANSI A58.1 or physical simulation which may include wind tunnel testing.

(S-601-4.2)

Ground Mounted Collectors

Wind loading on ground-mounted flat plate collectors and their support structures shall be determined in the same manner as that for roof-mounted flat plate collectors. Where flat plate collectors are mounted on open racks, equivalent roof area wind loads shall be those given for nonenclosed structures as given in Section 6.6, ANSI A58.1, taking into account local terrain characteristics.

(S-601-4.4)

Exposed Storage Tanks

Wind loads on exposed storage tanks shall be determined in accordance with ANSI A58.1.

(S-601-4.5)

SNOW LOADS

Flat Plate Solar Collectors Mounted on Roofs and Walls

Snow loads acting on flat plate solar collectors or caused by their installation shall be those required for roofs as specified in Section 601-5 of the MPS or as modified in paragraphs S-601-5.1.1, .2, and .3 below.

(S-601-5.1)

Flat plate collectors that are mounted with their cover plates and back surfaces parallel to the surface of a roof, and those that are mounted at an angle to the surface of a roof, on open or closed racks in a saw-tooth arrangement shall support the snow loads that would otherwise have been imposed on areas of the roof covered by the collectors. Where collectors are mounted with their cover plates forming steep slopes, shedding of snow from the collector may cause snow to accumulate at the base of the collector or other hazardous conditions which shall be considered in the design of the roof.

(S-601-5.1.1)

Flat plate collectors mounted at an angle to the surface of a wall, and supported by the wall, shall be designed to support the same snow loads as an equivalent roof eave area.

(S-601-5.1.2)

Consideration shall be given to the potential local accumulation of snow under flat plate collectors.

(S-601-5.1.3)

Roof Loading

A single or multiple saw-tooth array of collectors may cause severe drifting between each mounted collector (and under open racks) in addition to the snow load on the cover plates. These unusual snow loads must be determined on the basis of local snow conditions.

(S-601-5.2)

possibly quite heavy elements may be located in elevated positions in buildings. Collector arrays on roofs, water tanks in attics, thermal storage masses in walls or roofs (in passive systems) all present potential seismic hazards which are somewhat unusual for residential construction.

SEISMIC LOADS

General

Seismic design requirements for the mechanical and electrical components of solar energy systems are covered in this section. Architectural and structural components shall be designed in accordance with MPS Section 601-9. The requirements of this section shall apply to the erection, installation, relocation, or replacement of, or addition to any mechanical or electrical component of a solar system. If elements of the solar energy system are attached to any existing structural element, or if parts of any existing structural element are modified or replaced with parts different in size and weight, the element, as well as its connections to the building shall be redesigned to comply with the seismic design requirements of Section 601-9 of the MPS.

(S-601-6.1)

Mechanical and Electrical Components

For those buildings required to be designed for earthquake by Section 601-9 of the MPS, mechanical and electrical components of solar energy systems shall resist seismic forces as specified for parts and portions of buildings in the latest edition of the "Uniform Building Code" (UBC) [1]. The value of C_p used in the UBC to establish the seismic force shall be taken from Table S-601-6.

The design of all connections between the mechanical or electrical components and the structural frame shall allow for anticipated movements of the structure. The details of the connections shall be made a part of the contract documents.

Commentary: Mechanical or electrical components of a solar system are subjected to seismic forces generated by their mass and may also be influenced by interaction with elements of the structural system.

(S-601-6.2)

Hail impact represents another potential hazard from flying glass. With the exception of that portion of the U.S., the central hail belt, the criterion which follows establishes a level of performance essentially comparable to that desired for conventional roofing. In the hail belt, where hazard is greater, the performance level is somewhat increased.

HAIL LOADS

The cover plates, lenses, and reflector surfaces of solar collectors shall be protected against or resist the perpendicular impact of a single hailstone of the magnitude stipulated below falling at its terminal velocity.

[1] The "Uniform Building Code" is published by the International Conference of Building Officials, Whittier, California.

TABLE S-601-6

Part of System	Direction of Force	Value of $C_p \frac{1/}{2/}$
Storage tanks, pressure vessels, boilers, furnaces, absorption air conditioners, other equipment using combustible or high temperature energy sources, electrical motors and motor control devices, heat exchangers	any direction	0.12 when resting on ground 0.20 when connected to, or housed, elsewhere in the building.
Flat plate and concentrating solar collectors	any direction	0.20
Transfer liquid pipes larger than 2-1/2 in. diameter	any horizontal direction	0.12

1/ For flexible and flexibly mounted equipment and machinery, appropriate values of C_p shall be determined by a properly documented dynamic analysis, or by dynamic testing, using appropriate excitation spectra approved by HUD. Consideration shall be given to both the dynamic properties of the equipment and machinery and to the building or structure in which it is placed.

2/ WHEN LOCATED IN THE UPPER PORTION OF ANY BUILDING WHERE THE H/D RATIO IS 5:1 OR GREATER THE C_p VALUE SHALL BE INCREASED BY 50%

WHERE H = HEIGHT IN FT. OF THE PART OF THE SYSTEM ABOVE THE BASE LEVEL OF THE BUILDING

D = THE DIMENSION OF THE STRUCTURE IN FEET IN A DIRECTION PARALLEL TO THE APPLIED FORCE.

Terminal velocities for various hail sizes are given in Table S-601-7 [2]. Compliance with this provision shall be based on documented past hail loading performance or NBS Building Science Series BSS 23 [3] or analytical procedures acceptable to HUD.

Commentary: The correlation of hail size with mean annual number of days with hail was determined using data relating the probability of occurrence of hail particle size to the number of days with hail (tabulated in Ref. [4]), and limited statistical information relating the local area covered by hailstorm, and the regional area for which statistical data are compiled. The hail size indicated has a 5% probability of being exceeded in any one year (estimated 20 year recurrence interval). The hail requirements in this section are based on available information which does not contain physical test data. Therefore, local hailstone loading performance should be considered in implementing the requirements of this section.

The impact from the vertical terminal velocity is used as a measure of the effect of hail falling with or without horizontal wind. It is possible that a larger impact could occur on surfaces sloped from 30° to 60° if the maximum particle diameter occurred simultaneously with high horizontal wind velocity perpendicular to the surface. It may be overly conservative for particles over 1.5" impacting on near vertical surfaces. However, due to the lack of information on this phenomenon and the low probability of its occurrence, it is assumed that the terminal velocity gives the best measure of impact force consistent with the present state-of-the-art.

The loadings specified in this section to determine collector performance closely parallel those that conventional asphalt shingles and built up roofing are expected to withstand for all but the mid-continent hail belt.

DYNAMIC LOADS

Dynamic loads resulting from sun tracking solar collectors or other moving equipment shall be taken into account in the design of the dwelling frame.

(S-601-8)

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- [1] Baldwin, J. L., "Climates of the United States," U.S. Dept. of Commerce, Washington, D.C. (1973).
 - [2] Mathey, R. C., "Hail Resistance Tests of Aluminum Skin Honeycomb Panels for the Relocatable Lewis Building, Phase II," NBS Report 10193, National Bureau of Standards, Washington, D.C. (1970).
 - [3] Greenfield, H., "Hail Resistance of Roofing Products," Building Science Series 23, National Bureau of Standards, Washington, D.C. (August 1969).
 - [4] "Storm Data," U.S. Dept. of Commerce, National Oceanic and Atmospheric Administration, Environmental Data Service (monthly periodical).

Diameter in	Weight gm	Weight lb	Terminal Velocity ft/sec.
1/2	0.98	0.002	51
3/4	3.30	0.007	62
1	7.85	0.017	73
1 1/4	15.33	0.034	82
1 1/2	26.50	0.058	90
1 3/4	42.08	0.093	97
2	62.81	0.138	105
2 1/4	89.43	0.197	111
2 1/2	122.67	0.270	117
2 3/4	163.28	0.360	124
3	211.98	0.467	130

from: Mathey, R.C., "Hail Resistance Tests of Aluminum Skin Honeycomb Panels for the Relocatable Lewis Building, Phase II," NBS Report 10193, National Bureau of Standards, Washington, D.C., 1970.



FIGURE S-601-7

from: Baldwin, J. L., Climates of the United States, U.S. Department of Commerce, Washington, D.C., 1973.

THERMAL DISTORTION

Thermal distortion of the mechanical or structural components of the solar system shall not cause premature failure or degradation in system performance greater than the design limits.

Thermal distortion of the solar system, including that occurring during periods of stagnation, shall not cause damage to the system or the supporting dwelling structure.

Commentary: Expansion coefficient data for cover and absorber plate materials are listed in Appendix Tables B-1 and B-3.

(S-601-9)

COLLECTOR COVER PLATES

Deflection or local distress of cover plates resulting from the maximum design loading shall not allow the cover plate to become separated from the unit nor result in degradation in collector performance greater than the design limits. This shall be demonstrated by analysis or physical simulation.

Commentary: Since wind can come from any direction, there will be maximum pressure (inward) loading for units mounted on the windward side of an installation and maximum suction (outward) loading for those mounted on the leeward side (unless shielding is provided). Depending on the installation, suction loading can, and often does exceed pressure loading, hence, cover plate retainers must be adequately designed to prevent them from being separated from the collector frame or induce failure of the cover plate by suction loading.

(S-601-10)

or these surfaces such that moisture leaks occur
resistant surfaces.

(S-601-11)

STORAGE TANKS

Design and Fabrication

Storage tanks shall be designed and fabricated to standards embodying principles recognized as good engineering design and fabrication practice for the materials used. These standards shall include those listed in Appendices C and E of the MPS and others as approved by HUD.

Tanks containing soil or rock like materials shall be designed for lateral pressures in accordance with accepted principles of soil mechanics.

(S-601-12.1)

Testing

Each liquid storage tank shall be tested in accordance with section S-615-10.10 to prove that leakage does not occur. Storage tanks designed to contain only dry heat storage material need not be leak tested unless a safety hazard can result from a storage tank failure.

(S-601-12.2)

Environmental and Vehicular Loading

In addition to meeting the design, fabrication and test requirements, stipulated in the preceding paragraphs of this section, storage tanks shall meet the following loading requirements.

(S-601-12.3)

Above Ground

Unsheltered storage tanks shall resist loads resulting from snow, wind, hail, thermal, and seismic loading. Sheltered (completely enclosed) tanks need only resist seismic loading.

(S-601-12.3.1)

Underground

Underground tanks shall resist soil and hydrostatic loads and foundation loads transmitted to them and they shall be anchored to prevent flotation resulting from flooding or high ground water level when the tanks are empty. For sites subject to commercial traffic or heavy truck traffic, storage tanks shall resist the wheel loads transmitted to them as specified in AASHTO H20-44, with no impact. For areas subject to other vehicular or human traffic, the pertinent loads stipulated in section 601-4.3 of MPS 4910.1 or 4920.1 shall be resisted.

Commentary: The criterion specifies the level of vehicular traffic for which buried components should be designed in cases where heavy vehicular traffic is anticipated to occur in service for purposes of access. The H20-44 truck is considered to be representative of load levels associated with heavy vehicles such as trucks for repair, maintenance, moving, and delivery of fuel.

(S-601-12.3.2)

that are readily accessible and the build up of ice and snow on collectors. Relevant provisions that have not already been discussed are as follows:

Components of solar systems which are accessible, located in the areas normally subjected to occupant traffic and which are maintained at elevated temperatures shall either be insulated to maintain their surface temperatures at or below 140 F at all times during their operation or be suitably isolated. Any other exposed accessible components that are maintained at temperatures above 140 F shall be identified with appropriate warnings.

(S-600-6.3)

All domestic hot water systems shall be equipped with means for limiting temperature of the hot water for personal use at fixtures of 140 F.

(S-615-10.6)

In a companion document developed specifically for solar domestic hot water installations [5] storage tank overheating is addressed. Solar heated hot water tanks can reach temperatures much higher than those that would normally occur with conventional tanks, e.g., under low use conditions.

Thermal storage shall be protected against maximum temperature, pressure and vacuum in accordance with the provisions of S-615-7.4.1.

Commentary: During extended periods with no draw, solar DHW systems can supply thermal energy to such an extent that dangerously high temperatures may be reached in storage tanks. To avoid this, thermostatically controlled valves or other methods may be used to prevent undesired collector heat from entering storage. Such provisions may require collectors to be stagnation tolerant or provide heat dumping capability in the collector circulation loop. In any case, maximum tank temperature should be limited to 180°F

Personal hazard and system impairment due to snow and ice condition can be created by solar installations.

In areas which have a snow load of 20 pounds per square foot or greater required by local codes, provision shall be made over entrances and locations of pedestrian and vehicular ways to restrain or deflect sliding snow and ice masses which may slide off elevated solar system components.

Commentary: Solar system components may often include smooth slippery surfaces located in elevated positions at steep angles. These elements may heat up rapidly and loosen masses of snow or ice which may slide-off. Means should be provided to prevent a hazard to people or property. Methods such as deflectors, restraints, low friction materials or design of "safe fall" areas (pedestrian or vehicular ways spaced away from the building) should be considered

(S-304-3)

The design of solar buildings and systems shall provide for the possibility of formation of ice dams and snow build up.

Commentary: In very cold climates, water flowing off a warm collector may freeze on cold surfaces immediately below it (such as exposed eaves), thereby forming an ice dam which can cause water to back up under roofing or into the collector itself. This may be moderated by methods such as elimination of the cold surface or provision of an impervious surface such as continuous flashing. Snow sliding off a collector may pile up at the bottom and cover part of the collector. This would have a tendency to reduce the efficiency of the collector and increase the possibility of thermal breakage of glass in the collector. This may be moderated by methods such as the provision of space below the collector for snow pile up or by the installation of heating cables.

(615-2.1.6)

Glazing may be located in elevated and exposed positions increasing glass. The glazing may also be located adjacent to pedestrian traffic areas and in passive direct gain installations, glazing unbacked by a readily visible absorber presents a risk similar to that found in the glazing used in conventional window walls.

The materials used as glazing for cover plates must meet the following requirements based on materials properties as well as safety considerations. The safety requirements are made with respect to the physical location of the glazing and the exposure risk of persons nearby.

Commentary: Appendix Table B-1 lists properties of a number of materials that have been used for cover plates.

(S-515-2.2.1)

All glazing materials shall be of adequate strength and durability to withstand the loads and forces required by Section S-601 of this document.

(S-515-2.2.1.1)

Applications include windows which act as cover plates for solar collectors, both integral with dwelling construction and as freestanding components.

- a. Glazing materials other than those specified in b or c below, shall meet the intent of the requirements for glazing in MPS Section 508-8.3.

Commentary: Consumer Product Safety Act, Part 1201, was published in the Federal Register January 6, 1977 and will become effective on July 6, 1977 (except for fire retardant glazing required by ordinance for which the effective date is January 6, 1980). This standard contains mandatory safety standards for architectural glazing materials.

Film-type glazing materials for the outermost cover plate, if unsupported, may be unacceptable if they can be deflected under load, e.g., a person's hand pushing against the glazing may present an opportunity for exposure of the film (and the person's hand) to hot surfaces such as the absorber plate. Also there is a probability of exposure to impact which may result in tearing of the film.

- b. Glazing materials with slopes less than 45° which extend below 6' 0" (from ground level) shall be safety glazed or otherwise protected against impact of falling bodies.

Commentary: This commonly refers to glazing on which children may climb or against which a passerby may fall.

- c. Glazing panels which are an integral part of a roof or rack-mounted system on a roof, not routinely accessible by the occupant, shall meet the requirements of Section S-601.

Commentary: Annealed glass or films may be acceptable.

(S-515-2.2.1.2)

Protective measures for maintenance personnel include the following:

Where access for service or cleaning of solar subsystems requires a person to balance on a narrow or (steeply) sloping surface, provisions shall be made for securing a life-line, guard-rail, or other personal protective device.

(S-600-6.6)

Solar energy components located on the site shall be accessible for cleaning, adjusting, servicing, examination, replacement or repair without trespassing on adjoining property.

Commentary: Components should not be located unnecessarily under buildings or roads or in other places which are difficult to reach. Storage tanks in particular are large and may need periodic replacement or inspection.

COLLECTORS ON ROOFS OVER 2 STORIES MUST HAVE ACCESS PROVIDED FOR
CLEANING AND MAINTENANCE.

COMMENTARY: THE USE OF PORTABLE LADDERS IS NOT CONSIDERED TO BE ADEQUATE
UNDER THESE CIRCUMSTANCES.

(S-309-1)

Personal hazard may also result where blinding reflections, sharp edges, and heavy traffic situations are present. These are noted in the following:

Special considerations must be given to assure that elements of the solar system do not create unnecessary safety hazards to users.

Commentary: Hazards which require special attention include the reflection of sunlight which creates visual distraction, the projection of sharp edges which influence the movement of people near free-standing collectors and the proximity of solar components to recognized architectural hazards such as exterior overhangs, stairs, ramps, landings, doors, etc.

(S-303-2)

9. OTHER PROVISIONS

A number of other provisions are directly related to health and safety, e.g., protection against vermin and rodents, location and identification of emergency controls and provision of 100 percent back up with auxiliary energy.

Solar energy systems (including piping, fixtures, appliances, and other equipment) should not contribute to the entry or growth of vermin or rodents. Maintenance of physical barriers, minimization of concealed spaces conducive to harboring vermin or rodents, provisions of access for cleaning should be in accordance with applicable codes such as Section 2.13 of the National Standard Plumbing Code.

(S-600-6.8)

Main shutoff valves and switches shall be conspicuously marked and placed in a readily accessible location, in the same manner as electrical service panels, in accordance with Section 240.24 of NFPA 70, and MPS, Section 616.

(S-615-14.2)

The thermal energy contribution provided by solar energy shall be backed up 100 percent with an auxiliary thermal energy subsystem which will provide the same degree of reliability and performance as a conventional system.

Commentary: The uncertainty in the availability of solar energy during inclement weather requires complete back up of the solar energy contribution to meet comfort and hot water standards.

(S-615-1.2)

There are many other provisions, too numerous to mention, related to the durability/reliability of materials that have health and safety implications should a failure occur. In addition, reference to applicable standards is used in the MPS and IPC documents as a means of ensuring safety.

2. "Interim Performance Criteria for Dwellings," January 1, 1975, prepared for HUD by NBS.
3. "Interim Performance Criteria for Solar Heating and Cooling Systems in Commercial Buildings," prepared for ERDA by NBS, NBS Report NBSIR 76-1187, November 1976.
4. "Intermediate Minimum Property Standards for Solar Heating and Domestic Hot Water Systems," prepared for HUD by NBS, NBS Report NBSIR 76-1059, April 1976 (Draft for comments; no longer available in print).
5. "Intermediate Standards for Solar Domestic Hot Water Systems/HUD Initiative," prepared for HUD by NBS, NBS Report NBSIR 77-1272, July 1977.

Chairman: Robert Flugum
Co-Chairman: George Chang

Nearly all man-made systems cause some environmental effects. The operating electrical utility realistically seeks to identify these effects, develop mitigating measure where necessary, and make management decisions which achieve a balance between maintaining low electricity costs, protecting the quality of the environment, and assuring the reliability of service demanded by its customers. This paper described the significant environmental issues, both biological and non-biological, in construction, operation, and maintenance of the Pacific Northwest Transmission System. Discussion covers the influence on system planning alternatives, design options, and measures to protect the environment. A case for advancement of transmission technology to 1100 kV is presented.

AUDIBLE NOISE FROM HIGH-VOLTAGE TRANSMISSION LINES: PSYCHOACOUSTIC FINDINGS

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Extra-high voltage (EHV) transmission lines often produce audible (corona) noise during moist weather conditions. A series of experiments was conducted to determine how aversive this noise is to people. These experiments employed recorded samples of corona noise, other environmental noises and artificial reference stimuli. Corona noise samples were found to be equally preferred to other noise samples that were approximately 10 dB higher in sound pressure level than the corona noises. Corona noise was significantly less preferred than the ambient noises occurring near the transmission lines. These findings were true regardless of whether or not the research participants knew that the source of the corona noise was a power line. There were significant differences in preference for different samples of corona noise recorded from different lines. These differences were also observed when the corona noise samples were adjusted to have equal A-weighted sound levels. High-frequency components of corona-noise spectra (>500 Hz) contributed most to the aversiveness of the noise. While all of the commonly used frequency weighting scales correlated strongly with preference, D-weighted sound level provided the highest correlation with the preference data and the smallest standard error bands.

The increasing need for ultra high voltage power lines raises the serious question of what effects exposure to high intensity electric fields will have on both human beings and infra-human species. A preliminary study is underway to develop and thoroughly test the experimental protocols and apparatus which are planned for a major study of the behavioral and biological effects of high intensity 60 Hz electric fields.

The African baboon (Papio anubis and Papio cynocephalus) has been chosen as an animal model for the examination both of individual performance (operant conditioning) and natural (social) behavior. We are especially interested in possible effects on the higher integrative functions of the central nervous system. The behavior of baboons is being observed before, during, and after exposure to 60 Hz electric fields at a maximum intensity of 60 kV/m.

Presently, the first group of subjects is being exposed. This paper covers the apparatus, experimental protocol and planned future studies. The studies will first determine what kinds of effects (if any) occur at a 60 kV/m field intensity and then determine the intensities of exposure at which effects are just barely noticeable. This and other similar studies should provide the basis for future exposure standards.

ELECTROMAGNETIC FIELDS - TISSUE INTERACTIONS

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Absorption of energy from oscillating environmental electromagnetic fields by living organisms is determined by the degree of coupling of the organism to the imposed field. It is thus dependent on the capacitance of the body to its surroundings or to free space, and will increase with the field frequency. Typical coupling capacitance values for the human body are in the range of 50 pf. Resonant interactions with the whole body relate to body size as its dimensions approach a half wavelength and result in tissue "hot spots" at current antinodes. Resonant effects for man occur around 40 MHz and for the human head around 400 MHz. Brain tissue gradients of 50 to 100 mV/cm occur at a field frequency of 450 MHz, 1.0mW/cm² (E gradient in air 60 V/m). By contrast, a 60 V/m, 10 Hz field induces a brain tissue gradient of only 10⁻⁶ V/cm. Behavioral, neurophysiological and biochemical data indicate a sensitivity of nervous tissue to environmental electromagnetic fields substantially weaker than those producing significant tissue heating (>0.1C). Sharks and rays navigate and seek prey by using electric gradients as weak as 10⁻⁸ V/cm from DC to 10 Hz. Bird navigation using the horizontal component of the earth's magnetic field appears dependent on flight

These "windows" are clear and confirmed by independent studies of binding and release of calcium from brain tissue. They strongly indicate a hitherto undisclosed class of nonequilibrium, long-range interactions in brain tissue, arising in coherent states of biological macromolecules. Blockade of membrane ionic channels with lanthanum now supports the hypothesis that cell membrane surface glycoproteins, which behave as a polyanionic sheet, are the site of weak electric field transductive coupling. Amplitude "windows" in the field sensitivity and effects of altered hydrogen ion concentrations suggest a role for proton "tunneling" in these effects. (Supported by Bureau of Radiological Health Grant USPHS 1R01678-01 and by the National Institute of Environmental Health Services, Department of Energy and Office of Naval Research under Contract N0014-76-C-0421).

EFFECTS OF ELECTRIC FIELDS ON SMALL LABORATORY ANIMALS

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A multidisciplinary research team consisting of physical and biological scientists is conducting a broad and comprehensive study to screen for effects on rodents of acute and chronic exposure to 60 Hz electric fields. Systems were built for the simultaneous exposure of 288 rats and 576 mice to well defined, uniform 60 Hz electric fields free from secondary phenomena such as corona, ozone, shocks and hum. To date, over 600 parameters have been assessed in several thousand rats and mice exposed at 100 kV/m for up to 60 days. No statistically significant, reproducible effects were observed in hematology or serum chemistry parameters, immunological competence, organ and tissue morphology, bone growth and structure, body and organ growth, metabolic status, cardiovascular function, endocrine function, reproductive performance, fertility, fecundity, fetal development or postnatal development. Significant behavioral and neurophysiologic effects have been observed. In short duration behavioral tests (45 minutes), contingently exposed rats spent more time out of the electric field than in it at field strengths ≥ 90 kV/m. In longer tests (24 hours, 12-hour light: 12-hour dark), rats contingently exposed at 75 or 100 kV/m spent more time out of the electric field than controls during both the light and dark periods. However, rats contingently exposed at 25 or 50 kV/m spent more time in the field than controls, but only during the 12-hour light period. In the neurophysiologic tests, it was found the fatigue of sympathetic ganglia to repeated stimulation (time to half-amplitude) is slower in rats exposed to 100 kV/m for 30 days than in sham exposed rats. Also, the nerve conduction velocity of C fibers (unmyelinated) of the vagus nerve is significantly ($p < 0.01$) faster (10%) in rats exposed to 100 kV/m for 30 days than in sham exposed rats. The strength-duration curve of the vagus nerve indicates a lower threshold (i.e., increased excitability) in exposed rats. The action potential decays slower in C fibers of the vagus from exposed rats. Experiments are now in

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Consideration of environmental issues as an integral part of planning for technology development is mandated by the National Environmental Policy Act (NEPA) of 1969. In the Interim Management Directive of January 1978, the Department of Energy (DOE) established policy to identify, characterize, assess and mitigate real and potentially adverse environmental impacts in all DOE programs. In compliance with these regulations, the Division of Energy Storage Systems periodically reviews all energy storage projects to ensure that environmental issues are being appropriately considered. This paper provides an overview of the planning approach to integrate environmental considerations into the overall energy storage R&D program development, as well as presents methodology to identify and prioritize environmental concerns and potential benefits. Examples of specific energy storage projects are discussed.

COMPRESSED AIR ENERGY STORAGE (CAES) ENVIRONMENTAL CONTROL CONCERNS

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This work described the technologies of compressed air energy storage and some of the environmental concerns associated with siting, construction, operation and decommissioning of such a system. Also described is an ongoing research program, the goal of which is to evaluate methods to control the effects of these environmental factors.

ABSTRACT

Nearly all man-made systems cause some environmental effects. The operating electrical utility realistically seeks to identify these effects, develop mitigating measures where necessary, and make management decisions which achieve a balance between maintaining low electricity costs, protecting the quality of the environment, and assuring the reliability of service demanded by its customers. This paper describes the significant environmental issues, both biological and non-biological, in construction, operation, and maintenance of the Pacific Northwest Transmission System. Discussion covers the influence of system planning alternatives, design options, and measures to protect the environment. A case for advancement of transmission technology to 1100 kV is presented.

INTRODUCTION

BPA operates over 12,600 miles of transmission lines which involve over 200,000 acres of right-of-way and 353 substations in 5 states. The environmental impact of these facilities is very much a concern to BPA. Efforts are made to locate and operate these facilities so as to minimize adverse impacts.

As a Federal Agency, BPA is subject to requirements of several laws and regulations which pertain to environmental protection. For example, the "National Environmental Policy Act of 1969" requires all Federal agencies to prepare a statement of environmental impacts for all proposed major projects which could significantly affect the environment. This Act makes provision for public input into the Federal decision-making process. BPA's environmental specialists prepare Environmental Impact Statements for all major transmission line and substation projects. A sophisticated computer based transmission line corridor evaluation methodology is being tested at BPA which would provide for explicit identification of public concerns.

Another important act is the "Endangered Species Act of 1973", which forbids Federal agencies to carry out any activity which could jeopardize a species of plant or animal which has been officially determined to be threatened or endangered. BPA is presently engaged in formal consultation with the U.S. Fish and Wildlife Service to insure that a proposed BPA transmission line in Montana would not affect the threatened grizzly bear or the endangered bald eagle.

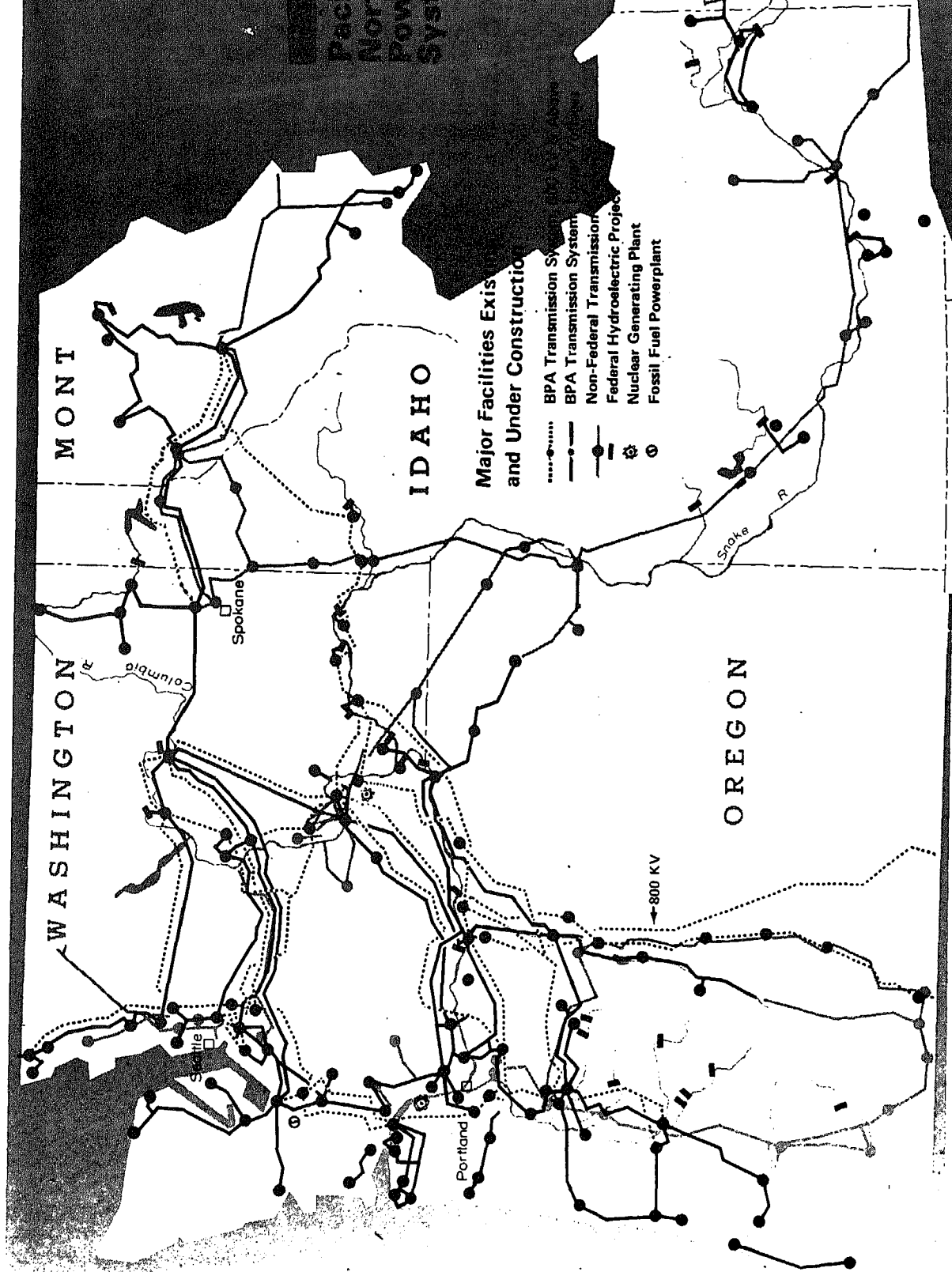
the length and number of transmission circuits and the geographical location of these circuits. Until the 1970's, most of the large generating plants were hydro and determined by natural sites along the Columbia River and its tributaries. See Fig. 1. This left little alternative to the system planner for location of generation. The average transmission length for the main hydro transmission system was 150 miles. These lines traversed agricultural lands and the Cascade Mountain forests.

In the early 1970's most feasible hydro sites had been developed and new generation consisted of thermal plants. These had more flexibility as to site selection. Extensive system studies were made to locate these as near to load centers as possible. For instance, the 1400 MW Centralia coal-fired plant, built in 1973, was sited 65 miles from Tacoma/Seattle, and the 1100 MW Trojan Nuclear Plant, built in 1976, was located 45 miles from Portland, Oregon.

Unfortunately, nuclear plants have also encountered many constraints and siting is no longer possible on the basis of minimizing transmission and consequent transmission environmental impacts. Public acceptance of the plants themselves is the controlling factor. Siting of nuclear plants near the load centers has not become a widely accepted practice in the U.S.A. However, from an environmental and conservation standpoint there is probably no other energy supply system alternative as clean and efficient as a nuclear plant near the load center with provisions for use of the waste heat.

Coal-fired plants similarly have been moved further to the east or at the coal fields in Montana, Wyoming, and Utah. With this trend transmission distances will increase and attain as much as 800 miles in the case of Colstrip to Seattle. Moving coal by rail or slurry lines are alternatives to electric transmission. Many opinions exist on the relative economics and environmental impacts of these alternatives. Because the Rocky and Cascade Mountains intervene between the coal fields and the coastal load centers, electricity has generally been preferred. Electric transmission does not produce continuous pollutants into the air along the way or at the receiving terminal like the other two alternatives. On the other hand, there is probably less opportunity for use of the plant waste heat unless industry or government gives more attention to this aspect. 1/

Another element in this system planning process which significantly influences the overall environmental impact of the Pacific Northwest Transmission System, is the reliability criteria for that system. Following the Northeast Blackout in 1964, regional reliability councils were formed. BPA participates in the Western System Coordinating Council (WSCC) and also the National Electric Reliability Council (NERC). BPA has aligned its own reliability criteria to reflect these Regional and National efforts. Unfortunately, reliability and environmental objectives are usually in conflict. For example, BPA's fundamental reliability requirements for transmission planning is: "With one



redundant transmission lines in the Pacific Northwest transmission network. The number of redundant components is proportional to the degree of reliability required. When our society demands a high level of service from the electric energy supply system for their lights, heat, comfort, and recreation, it is doing so at the expense of environmental quality. These demands require more generators, transmission lines, and support facilities to be built. In recognition of this fact, BPA has developed elaborate computer programs to test the performance of the power system for reliability. This has resulted in development of advanced techniques for achieving reliability goals without having to build as many additional transmission circuits. These techniques include installation of series capacitors in high voltage circuits, high speed relaying, low impedance transformers, development of a system braking resistor, specification of low impedance generators, and advanced control systems. BPA has one of the most modern utility control systems in the world, designed to anticipate problems and restore service after service interruption.

Another important element in system planning affecting the gross environmental picture, is the basic design of the transmission lines. With longer distances and higher capacities required, it is necessary to go to higher voltages. While the main grid in 1950 was 230 kV, today it is 500 kV. As shown in Fig. 2, this initially reduced right-of-way requirements by a factor of 7 as compared with continuing transmission at 230 kV. Latest double circuit 500 kV designs have cut this factor by another 3. BPA currently has a \$6,000,000 prototype line at Lyons, Oregon, operating at 1200 kV and a \$5,000,000 mechanical test line at Moro, Oregon. We expect 1100 kV will be the nominal transmission voltage in the late 1980's. It will reduce right-of-way requirements to one-thirty fifth of that required by the original 230 kV circuits. Purpose of the Prototype Projects is to evaluate economic and environmental acceptability. 2/

NON-BIOLOGICAL IMPACTS

For environmental impact statements, BPA divides the analysis into non-biological impacts and biological effects. These two categories are not mutually exclusive but serve as a basic division for analysis. The first group are mainly physical primary impacts of building or operating the line. The biological effects are secondary in nature and result from the lines electric field or maintenance chemicals.

Corridor

Increasing attention is given to locating new lines on existing multiple line corridors wherever practical. In fact, BPA policy is not to open any new corridors across the Cascade Mountains. This means that we will tear

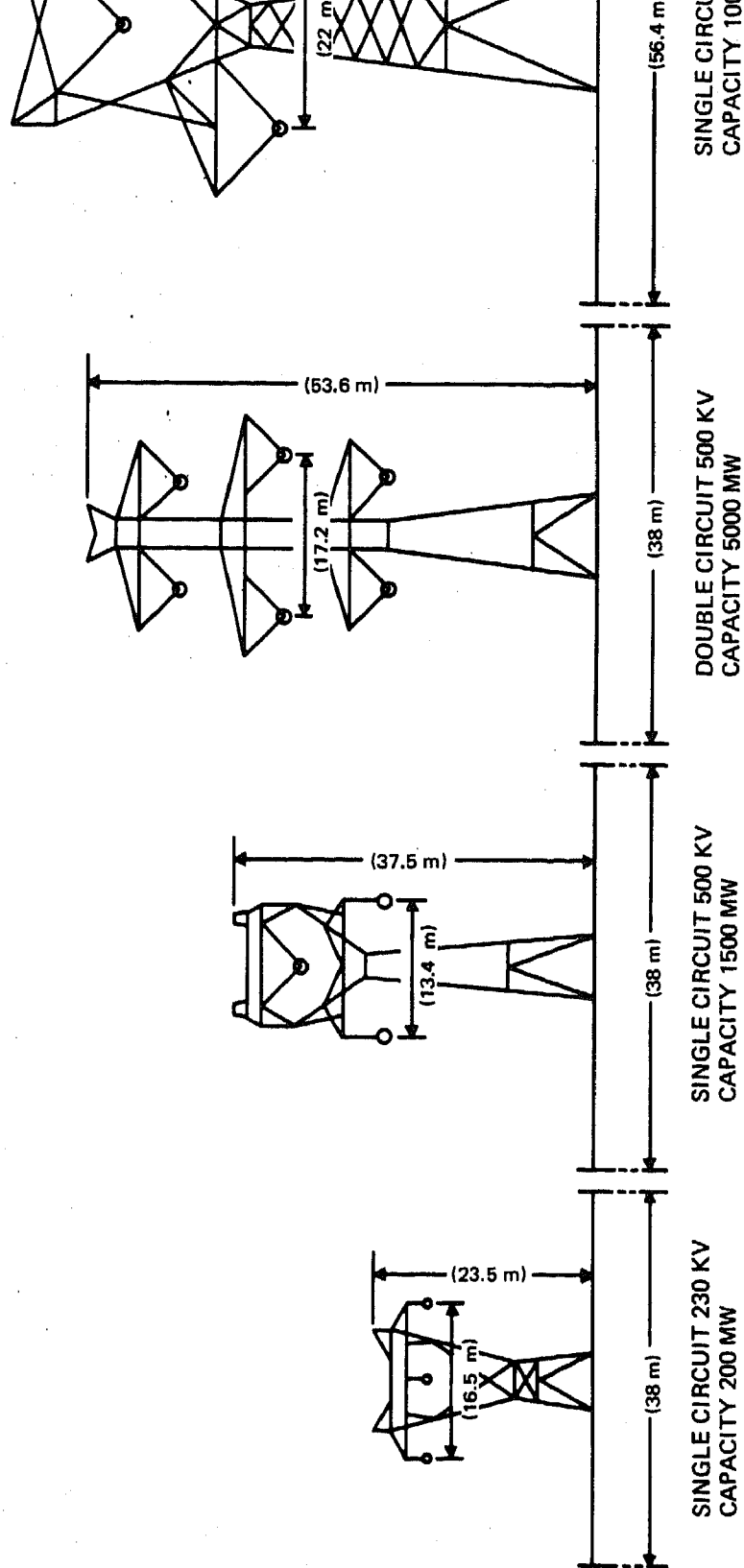


FIGURE 2 REDUCING LAND REQUIREMENTS THROUGH HIGHER CAPACITY LINE DESIGNS.

returned it to the open market when it is no longer economically acceptable routing. Increasing the power transmission capacity on existing corridors often requires innovations and additional expenses. Removal cost of old lines still in service often exceeds the cost of new right-of-way. Removal of the old line means more capacity must be built into the new line, meaning taller structures. Despite these immediate disadvantages, BPA is dedicated to the long-range principle of minimum new right-of-ways.

In addition to following existing power line corridors, increasing use is made of transportation corridors. Again, there are some disadvantages in this shared corridor approach. Some of the public complains of the visual impact of locating power lines along highways. This is done with sensitivity to the particular area involved. In urban areas we have used tubular and concrete structures. In natural areas we prefer lattice steel structures.

Where railroad corridors exist along a general line routing, we investigate feasibility of occupancy. This is often more expensive than a new right-of-way because of need to change railroad signaling and communication systems. We currently are developing special line designs which would facilitate supporting catenary wires for electrified railroads. This will lessen corridor impact by reducing the overall number of supporting structures for both power line and railroad.

Locating power line and pipelines on the same right-of-way requires special attention to interactions between the different systems. Each must be protected from the other. Ground currents from the power system can be hazardous to pipelines. Similarly, failure of gas lines can interrupt service of the power line. The special protective measures to allow joint corridor usage represent added cost but usually are accepted for the benefits of reduced land impacts.

Urban Land

Wherever possible BPA avoids locating transmission lines and substations within city limits and highly developed areas. This is to minimize disruption to people. In some instances communities have favored power line location in their area because it provides a green belt for their horse, a vegetable garden, kids, parks, etc. Thus, we cannot say that power lines always have negative impacts. In fact, in densely populated areas it may be an advantage. However, the utility must weigh this against greater liability risks from human encounters.

Forest

In the Pacific Northwest, particularly in the Cascade Range, much of the land is forested. Lines crossing forest lands require removal of essentially all of the non-deciduous fir and pine trees because of the high and rapid growth rate. This represents a substantial loss to forest product production as well

is taken through negotiations with the Forest Service to minimize erosion and disturbances to the vegetation. Unlike some areas in the East, it is usually necessary to maintain an access road to the lines because of the rapid vegetation growth. Many times these are shared roads with the logging industry.

Agricultural

The bulk of BPA lines are on either forest, agricultural, or grazing land. Agriculture is a compatible land use with power lines. While some farmers object to location of transmission structures in their wheat fields, we have generally found that the loss of arable land is very minor, consisting essentially of ground at the base of the structure. Crops are grown under the conductors and irrigation can proceed. Objections have come from spray pilots but the pilots usually maneuver under the high voltage conductors as long as BPA aligns the structures on multiple line right-of-way. We cannot identify any crop disallowed on BPA right-of-way, including Christmas trees.

Recreation

BPA allows many forms of recreation on our line right-of-ways, including golf courses, baseball-diamonds, motor cycle trails, hunting, etc. We generally try to avoid swimming pools, tennis courts, and enclosed facilities because of potential electrical hazards or impediments to maintenance and operation of the lines. However, examples in this category exist and have been specially equipped for human safety.

Visual Effects

Overhead transmission lines will normally be seen. The impact is subjective. Because most BPA lines are located outside urban areas, we use lattice steel structures. They are lowest cost; their gray galvanized steel gradually ages to blend with the skies and forest; and the lacing fades rapidly with distance as compared with tubular or boxed girder designs. In particular cases, such as the scenic Columbia Gorge, special measures were taken to reduce line visibility. There we used non-specular conductors and a special vinyl wash paint to dull visibility of the towers. In this case it was not possible to totally screen the line from highway views by location because the towers were taller than the trees. BPA uses a highly sophisticated computer program to evaluate views and published a set of guidelines to reduce visual impact of transmission facilities. 3/

Electrical

In this category are audio noise, radio interference, television interference, communication circuit interference, ozone production, energy losses, and electric/magnetic fields. All of these effects are controllable by the design

be insignificant providing other parameters are considered. Conductors are selected for long-range economics considering capital costs and energy losses. The electric/magnetic field values are not actually an impact in themselves but are currently the most controversial parameters because of potential secondary biological effects, to be treated later in this paper.

Books have been written on these potential impacts. 4/ This is a net result of extensive research and development on the subject by the industry over a number of years. Electrical performance of a new line design is now highly predictable for most weather conditions in the U.S.A. Tests at Project UHV, BPA 1200 kV Prototype Line, AEP, and others have extended this science to 1500 kV a.c. DOE is funding work on d.c. to the same values. The science is well established but much art remains. The art is in society agreeing upon acceptable audio noise and field strength levels.

BPA designs new lines to an audio noise level at edge of right-of-way of 50 dBA (L50) in rain. This is equivalent to noise from a passenger car at 100 feet or comparable to the sounds from rain falling upon deciduous tree leaves. For field strength we design to a maximum level of 9 kV/m at midspan under the line and 5 kV/m maximum at edge of right-of-way. This has been our practice on the 500 kV system with over 2500 miles in operation. The BPA 1200 kV Prototype Line conforms to these standards.

Line costs are inversely proportional to sound and field strength levels. If society would agree to higher levels in remote mountainous areas, for instance, costs could be reduced. Not only costs are affected by our choice of tolerable environmental impacts but the materials and energy to manufacture and construct the line are also affected. Society needs to reflect on the total environmental impact in making its choice, not just the short term impact on its ear, rates, and sense of feeling.

BIOLOGICAL EFFECTS

During the first years of preparing environmental statements, it became apparent that the data base for predicting the effects of transmission lines was deficient. In 1974 BPA formed a multidisciplinary Biological Studies Task Team to develop a test program for obtaining information on biological effects of transmission lines. The team began a review of literature on which to base research recommendations. The literature review and comments received from the public indicated a need to study the effects that may result from electrical properties of such lines.

A Research Program was developed to provide information on the biological effects of transmission lines primarily through field investigations. We are relying on laboratory research of others to supply information on possible long-term physiological effects which may result from exposure to electric

the environmental effects of transmission lines are a result of the combined effects of construction, operation, and maintenance activities. During line construction a heavy influx of men and machinery can represent a significant short-term disturbance. Once the line becomes operational, plants and animals on the right-of-way may be influenced by a linear cleared right-of-way, human activity on access roads, metal towers and conductors, electric and magnetic fields, audible noise, and chemically treated vegetation. The effects of this environment on different plant and animal species in different habitats has been the subject of a number of research projects at BPA and elsewhere.

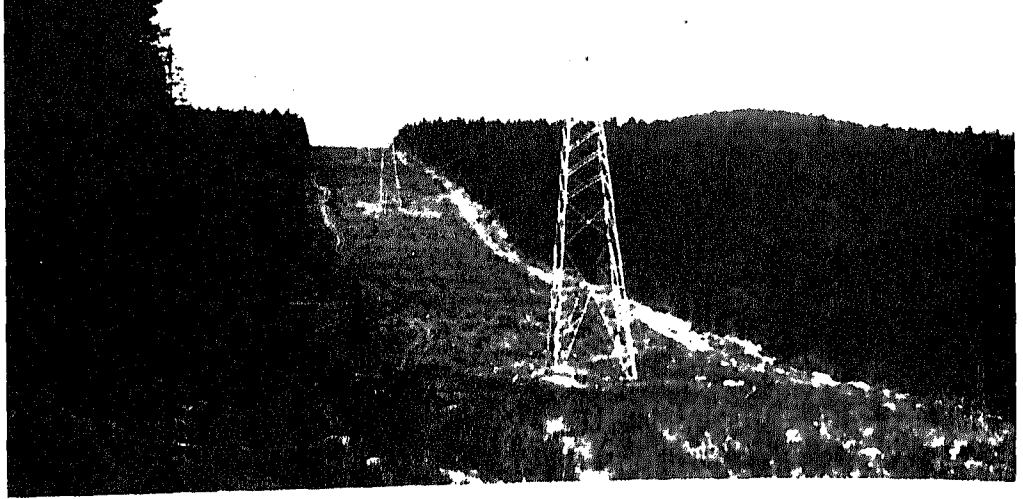
We will now describe some typical impacts on plants and animals which result from construction, operation, and maintenance of transmission lines based on BPA research findings and operational experience. Included will be examples of measures used to minimize or eliminate the occurrence of adverse impacts. More detailed information on these subjects can be found in four recent publications. 5/, 6/, 7/, 8/

Plants

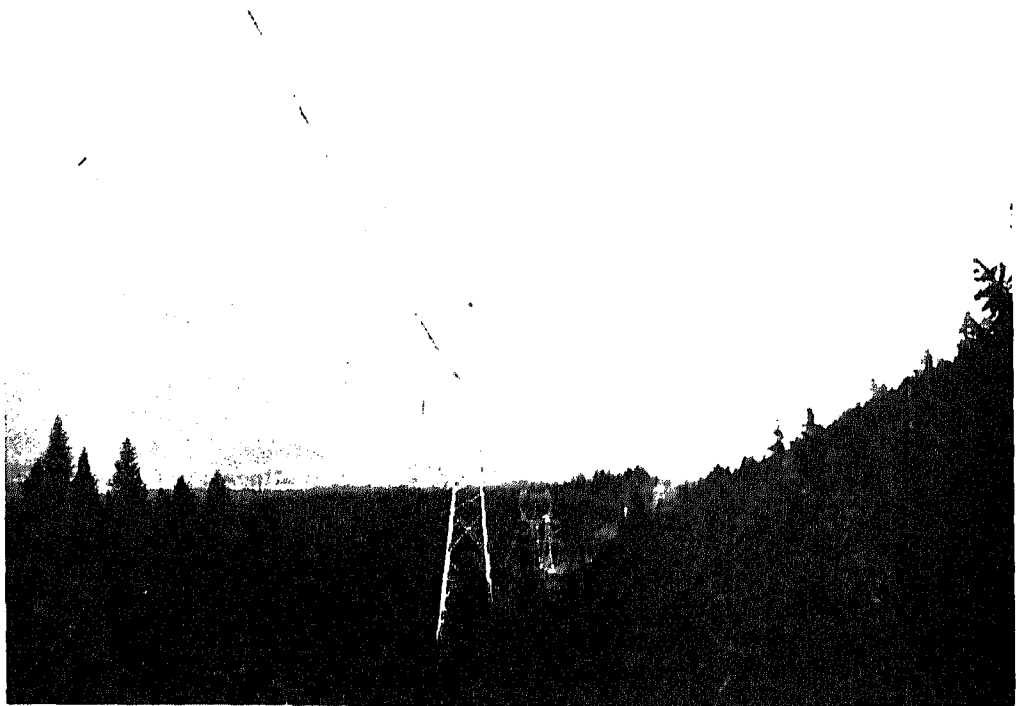
Brush and trees on transmission line rights-of-way are controlled so that they will not grow into conductors or impede restoration of service if outages occur. Vegetation management is accomplished in a variety of ways including both mechanical cutting and chemical treatments. The result in forested areas is that plant succession is maintained in a shrub grass stage.

Vegetation modification begins during construction when considerable disturbances can occur. Fig. 3 (a) illustrates earlier right-of-way clearing practices in 1968 where the entire right-of-way was stripped. Fig. 3 (b) illustrates present practices which leave as much low-growing vegetation as possible and more trees near the line. All vegetation may be temporarily removed at tower bases and where access roads are constructed. Such areas are often reseeded to facilitate vegetation regrowth. At times special seeding mixtures are used to increase forage values for wildlife.

Damage due to high electric fields has been noted on some trees growing very near to the BPA 1200 kV prototype line. Similar damage, due to induced corona, has also been reported for trees growing near lower voltage lines. The damage is slight compared to effects of maintenance activities, such as cutting or pruning of trees before they grow close enough to conductors to be damaged. No adverse effects of transmission line electric fields on over-all plant growth has been noted. A special photogrammetric program was developed at BPA to allow precise determination of trees which are to be cleared from the right-of-way. This results in a more "feathered" right-of-way edge compared to the stark, "straight edge" appearing rights-of-way often observed.



a. 1960's



b. 1970's

FIGURE 3 PROGRESS IN RIGHT OF WAY PRACTICES.

of the high reproduction potential and large population sizes of most insects, no significant adverse impacts are expected from construction of transmission lines.

Fish

BPA transmission lines cross innumerable aquatic habitats which are inhabited by a large variety of fish species. These include high quality streams used by anadromous species such as salmon and steelhead. Impacts on fish can occur primarily as a result of construction activities and right-of-way use by vehicles. Clearing and road construction activities can be especially detrimental unless special precautions are taken to prevent siltation and damage to stream banks.

Prior to construction, efforts are made to discuss stream crossings with personnel from appropriate state or Federal wildlife agencies. Options which are available to minimize impacts on fish include timing of construction, location of access roads, and use of prepared fords or culverts.

Because herbicides could affect fish and other aquatic organisms, these chemicals are not applied near water bodies although on occasion accidental drift of spray may occur in these areas. BPA sponsors an ongoing monitoring program of the movement and persistence of herbicides used on rights-of-way.

The electric field produced by transmission lines in water is generally below the level of detection by fish. No effects of this parameter on fish has been documented for BPA transmission lines.

Birds

Transmission lines can result in a variety of impacts on birds, both adverse and beneficial. Many species can be found on rights-of-way, especially where the right-of-way increases habitat diversity. Changes in vegetation influences bird nesting and feeding activities. For species which may require undisturbed forest habitat, a cleared right-of-way may prove undesirable.

Birds frequently use transmission towers for perching and nesting. Hundreds of nests of hawks, osprey, and other birds have been located during transmission line helicopter surveys. Many birds successfully rear their young on 500 kV line towers with apparently no ill effects due to electric fields which may be much stronger than those found at ground level.

Birds on towers may be highly visible and may be tempting targets for some illegal shooters. Not only are birds killed, but such shooting may damage insulators and other components.

Another negative aspect is bird collisions with transmission line conductors or groundwires. Although this does not appear to be a serious problem with BPA lines, considerable interest on this subject has developed in recent

Mammals

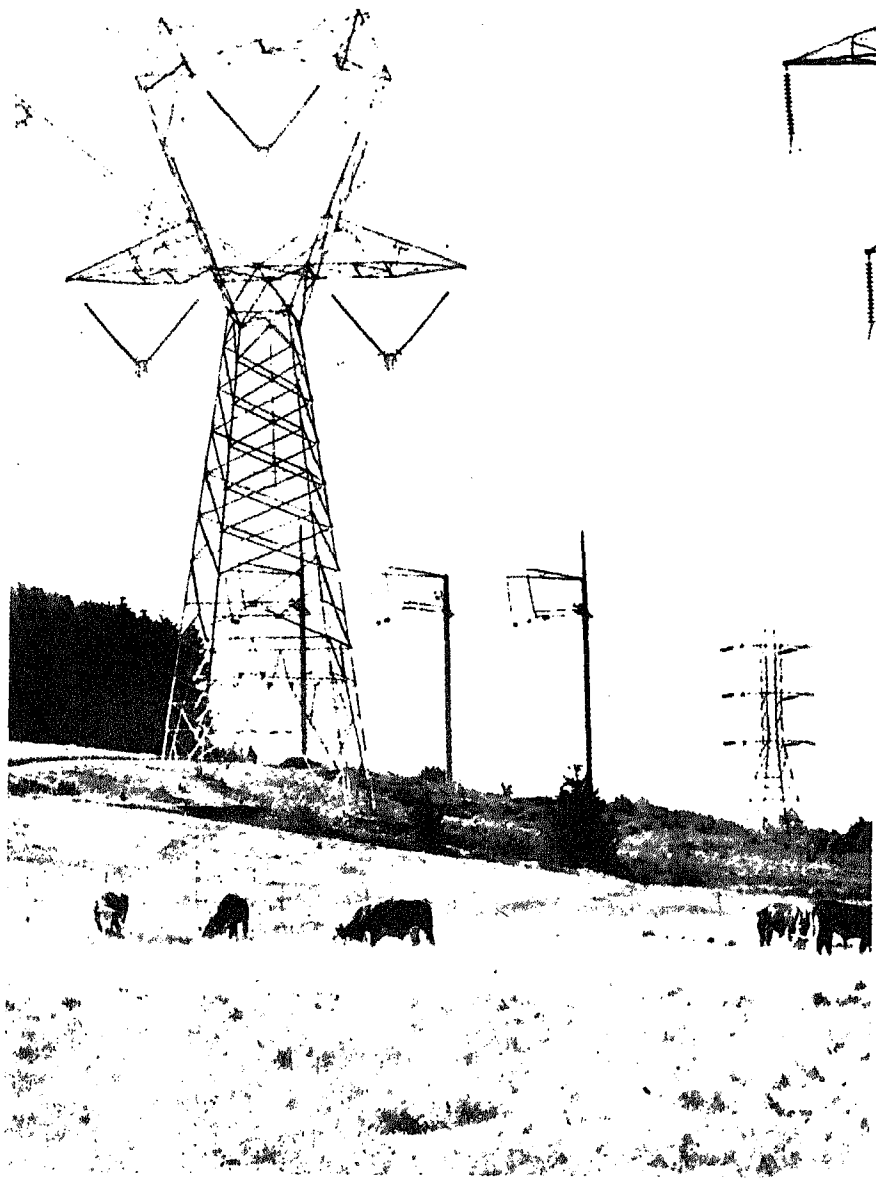
As with groups described above, impacts on mammals can take many forms. These impacts vary depending on the species of mammal, habitat requirements, quality and condition of habitat, and limiting factors acting on populations. Impacts begin with construction, the activities of which can cause some mammals to move out of the construction area. In so doing they may be more vulnerable to predation and other decimating factors. Some small mammals may be killed outright during construction.

These impacts can be partly reduced by scheduling construction to avoid critical times, e.g. during times big game are wintering, or during times of breeding and rearing of young. Information on such times is developed by BPA wildlife specialists in consultation with specialists from state and Federal wildlife agencies.

Once a line is constructed, maintenance activities keep the right-of-way in a shrub/grass stage which can attract big game animals to feed. Although this can be beneficial to these animals, the animals may be vulnerable during hunting seasons. Access roads and rights-of-way on some lines are heavily used by hunters. It appears, however big game animals quickly learn to avoid clearings after hunting season begins.

As with other animals, mammals are exposed to transmission line electric fields. Small mammals are usually exposed to minimal field strengths because of the shielding effects of vegetation. For animals not shielded, the transmission line can induce voltages and currents into the animals. These currents are usually below the level of perception although under certain circumstances, both wild and domestic mammals can receive mild shocks from fences and other objects on the right-of-way. Fences, water troughs and other such things are usually grounded by maintenance personnel to prevent shocks to animals and people.

The electrical effects of transmission lines (e.g. electric and magnetic fields, corona noise) do not appear to have any significant effects on animal behavior. As mentioned previously, concerns have been raised in recent years about the possible long-term physiologic effects of transmission line electric fields. Information being developed in laboratory studies indicate it is very unlikely fields of the strength produced by BPA lines are harmful to mammals or other animals. Because of continued public interest in this subject, which has implications for human health, BPA is conducting studies with Battelle Northwest Laboratories on cows, small mammals, birds, bees and plants at the Lyons 1200 kV Prototype Line shown in Fig. 4.



asked in recent years
adversely affect people.

In brief, much of the interest on this subject can be traced to Soviet studies done in the 1960's on EHV substation workers, which report adverse physiological effects attributable to exposure to high electric fields. ^{9/} As a result, regulations for Soviet substation workers now allow unlimited exposure to fields less than 5 kV/m and limit exposure times in fields higher than 5 kV/m. The Russians are conducting further research on which transmission line standards may be based. They feel standards for nonelectrical workers should be different because they are exposed infrequently to electric fields from transmission lines.

BPA personnel have met with Soviet engineers and scientists on a number of occasions. Results of these meetings, plus the experience of substation workers and linemen at BPA and other utilities in the United States, indicate the Soviet reports have little if any application to either substations or transmission lines in the U.S. Soviet substations can contain very high electric field strengths which can result in shocks, and other environmental factors which could be responsible for the reported health problems. This is usually not acknowledged by the Soviets.

No standards or regulations exist in the U.S. for exposure to 60 Hz electric fields. Transmission line designers have relied on responsible judgment and operating experience. The U.S. Environmental Protection Agency gathered information to determine if there is a need to provide guidance for radiation standards for transmission lines above 700 kV. The EPA feels, "Adverse health effects have not been demonstrated, and speculation about their existence is an inadequate basis to support public health action at this time", (Janes, 1976).

The large majority of published reviews on this subject conclude the likelihood is remote that transmission line electric fields pose any long-term health hazard. Research is presently being conducted to determine if there are levels at which biological effects may occur which would have an influence on design of future transmission lines.

Another subject involving people is the effect of electric and magnetic fields on cardiac pacemakers and other implanted medical devices. When a person touches an electrical tool or appliance, or is in an electric field, a low level current can flow in the person's body. Some pacemakers sense the low level voltages of the heart to function properly and extraneous currents and voltages of sufficient level can interfere with this function. Recent research at the IIT Research Institute indicates transmission line fields pose only a minimal risk to pacemaker wearers. This depends on the type of pacemaker and the way in which it has been implanted.

SUMMARY

It is obvious that no transmission lines can be built without some environmental effects. However, over 12,000 miles of 115-500 kV lines are in operation on the Pacific Northwest transmission system and some since 1939. Environmental experience has been acceptable. This has been possible by extensive research and care in the planning, design, construction and maintenance to minimize potential effects. Future trends in power supply will have a major effect on environmental effects. Development of mine-mouth coal plants remote from load centers in the Pacific Northwest, will increase transmission distances and resultant total environment exposure. This will require special attention to application of environmentally compatible locations and designs. Transmission at 1100 kV offers an attractive alternative for the future because of reduced right-of-way requirements and lower losses. More consideration needs to be given to nuclear plants located near load centers as an effective alternative having less overall environmental effects, particularly when waste heat is used for district heating and other uses.

- 2/ R. S. Gens, E. H. Gehrig, R. B. Eastvedt, 1979. "BPA 1100 kV Transmission System Development - Planning, Program and Objectives" (Proposed Paper IEEE Winter Power Meeting 1979)
- 3/ Department of Interior - Department of Agriculture, Feb. 1970. "Environmental Criteria for Electric Transmission Systems"
- 4/ Electric Power Research Institute, 1975. "Transmission Line Reference Book 345 kV and Above"
- 5/ Biological Studies Task Team, 1978. "Electrical and Biological Effects of Transmission Lines: A Review" (Second edition, revised, expected issue date is Nov. 30, 1978, U.S. Department of Energy, Bonneville Power Administration)
- 6/ J. M. Lee, Jr., and D. B. Griffith, 1978. "Transmission Line Audible Noise and Wildlife" (Pages 105-168 in J. L. Fletcher and R. G. Busnel 'Effects of Noise on Wildlife', Academic Press, New York 305 pp.)
- 7/ L. E. Rogers, R. O. Gilbert, J. M. Lee, Jr., and T. D. Bracken, 1978. "BPA 1100 kV Transmission System Development-Environmental Studies" (Submitted for presentation at the IEEE Winter PES Meeting, Jan. 1979, New York)
- 8/ J. M. Lee, Jr., L. E. Rogers, and T. D. Bracken, 1978. "Electric and Magnetic Fields as Considerations in Environmental Studies of Transmission Lines" (Paper presented at the 18th Annual Hanford Life Sciences Symposium, Biological Effects of Extremely Low-Frequency Electromagnetic Fields, Richland, Washington, to be published)
- 9/ T. P. Asanova, and A. I. Rakov, 1966. "The State of Health of Persons Working in Electric Field of Outdoor 400 kV and 500 kV Switchyards" (Hygiene of Labor and Professional Diseases, 'English translation available from Bonneville Power Administration')
- 10/ Bonneville Power Administration, April 1975. "Tips On How To Behave Near High Voltage Power Lines"

1. INTRODUCTION

The possible aversiveness of audible (corona) noise from extra-high voltage (EHV) transmission lines was investigated in a series of psychoacoustic experiments. Recordings of corona noise were made outdoors, generally at the edge of the property right-of-way. These recorded corona noise samples were then compared with other recorded environmental sounds, reference sounds, or spectrally-modified corona sounds, using a behavioral preference procedure. Results from three experiments, all employing the same general procedure, are presented here.

2. GENERAL METHOD

A. Research participants.

All three experiments employed paid volunteers, obtained from the Gaithersburg, Maryland, area through local newspaper advertisements. They were screened to be audilogically normal as tested with pulsed pure tones on a Békésy audiometer. Thresholds were within 15 dB of the reference coupler sound pressure level for normal hearing threshold (ISO, 1975). Ages ranged from 18 to 55 years (median age for females = 33; median age for males = 20). Experiment I employed 18 females and 8 males; Experiment II employed 21 females and 5 males; and Experiment III employed 17 females and 8 males. Altogether 77 people participated.

B. Field recordings.

Twelve acoustic spectra¹ were recorded on magnetic tape. The microphone was located 15.2 m (50 ft) from the noise source (50 ft from a point below the outer phase for transmission lines) at a height of 1.5 m (5 ft) above the ground, unless otherwise noted.

Apple Grove Corona - Audible noise was recorded from a test EHV (775 kV) ac transmission line located at Apple Grove, West Virginia, after a heavy dew.

Roanoke Corona - Audible noise was recorded from an operating EHV (765 kV) ac transmission line located near Roanoke, Virginia, during a steady rain.

Peru Corona - Audible noise was recorded in fog from an operating EHV (765 kV) ac transmission line located near Peru, Indiana.

Redmond Corona - Audible noise was recorded directly under a twin operating EHV (500 kV) ac transmission line in a quiet desert (clear weather) near Redmond, Oregon.

The Dalles Corona - Audible noise was recorded (clear weather) from a direct current (dc) test transmission line (600 kV) located near The Dalles, Oregon.

Country - Country sounds (birds singing with some distant truck noise) were recorded in an open field in Apple Grove, West Virginia.

Rain - The sound of steady, falling rain was recorded in a clearing in the woods near Roanoke, Virginia.

Air Conditioner - The sound from an operating window air conditioner was recorded in the middle of a large room.

Trains - The sound of passing freight train cars was recorded from a railroad in Gaithersburg, Maryland.

Octave - An octave band of white noise centered at 1000 Hz was recorded directly from an electronic generator and filter.

All of the above recordings of environmental noise must be regarded as isolated examples of the noise emitted by the particular source. For example, no attempt was made to sample statistically the noise from several different transmission lines under several different weather conditions in order to select a "typical" corona noise spectrum. Thus, the transmission line audible noise spectra employed in the present experiments may not be representative of the most prevalent corona sounds as heard in the environment, even for a given weather condition. The same is true as well for the tape-recorded sounds from the other noise sources.

C. Apparatus.

The same apparatus was used in all experiments. Field recordings for 11 of the 12 acoustic spectra (octave band excluded) were made with a portable system consisting of an air-condenser microphone, a preamplifier and power supply, sound level meter, and magnetic tape recorder. The twelfth spectrum, an octave band of noise, was tape-recorded on the same type of field recorder from a band-pass filter (24 dB/octave skirts) fed by a white-noise generator. The field recordings were edited to produce a five- to six-minute sample of relatively uniform sound and to remove any spurious man-made sounds.

The field recordings were copied, pairwise, from two matched field tape recorders onto two tracks of multitrack run-tapes. Four pairs of stimuli, each 320 s in duration, were recorded on a given run-tape. The run-tapes were played in different random orders during experimental test sessions to generate the sequences of stimulus pairs used in the acoustic "menu" procedure.

The pairs of spectra were gated by electronic switches arranged in two audio channels so that only one spectrum was presented at any given time. The rise/fall time of each electronic switch was 0.5 s, with a 0.5-s silent interval between alternations of the two members of a given pair of acoustic stimuli. Sound levels were controlled by programmable attenuators in each audio channel. The switched signal was fed through equalizers and power amplifiers to four loudspeaker systems concealed above the ceiling of the listening room. The gain for the two loudspeakers located above the windows of the room was 6 dB higher than the gain for the two loudspeakers above the inside corners of the room, to create the perception that the sounds were coming from the windows.

The participant sat in a realistic listening room outfitted like a living room. The plaster-walled room was 4.8 by 6.5 m (16 by 22 ft). It had an acoustically transparent, but visually opaque, suspended ceiling 2.4 m (8 ft) above a wooden parquet floor, and an acoustically hard cement ceiling another 1.2 m (4 ft) above the suspended ceiling. The room was constructed to be semireverberant so that a relatively diffuse and uniform sound field could be generated in the vicinity of the participant's head. Calibration of the acoustic stimuli, as

tave band field analyses, which are independent of the magnetic tape medium. Independent measurements of the acoustic spectra made with a 1/3-octave filter in the field corresponded closely with measurements of the reproduced acoustic spectra as heard by participants in the listening room. Most 1/3-octave band differences were less than ± 3 dB. Standard deviations for individual 1/3-octave bands as reproduced in the listening room ranged from 0.3 dB to 6.4 dB BPL (most less than 3 dB BPL). These standard deviations included both spatial variation near the participant's head and temporal variation over the 5-min stimulus duration. With the exception of a slight variation in the 100-160 Hz frequency region, the listening room conformed to the 1/3-octave band frequency response specifications (± 2 dB) for psychoacoustic tests stated in SAE AIR 1157 (1975). The background noise in the room had an unweighted sound pressure level of 53 dB (A-weighted sound level of 42 dB). Further details on the construction and calibration of the listening room may be found in an earlier report (Molino, *et al.*, 1977).

D. Behavioral procedure.

The "acoustic menu" procedure (Zerdy and Molino, 1974) was employed in all three experiments. In this procedure the participant sat at a desk in the listening room and read from a book. Pairs of acoustic stimuli were available for 5-min intervals, and the participant controlled which member of the pair was in effect at any given time. The proportion of available time that a person spent in a given stimulus provided a behavioral measure of preference.

On the first day of the experiment, the participant was allowed to select a book to read. The collection of available books included current best sellers and other popular light reading. The participant then read these specific instructions for the forced-choice "acoustic menu" procedure:

While you read at the desk, you will be hearing one member of a pair of sounds. If you want, you may change which sound of the pair you hear by pressing on the telegraph key marked "CHANGE." Whenever the lamp on the desk goes off, you must press one of the two keys in front of you within 5 seconds. If you press the key marked "STAY," the sound you are hearing will stay on; if you press the key marked "CHANGE," you will hear the other sound. You must press either the "STAY" or "CHANGE" key whenever the lamp goes off. You are also free to change the sound you hear at any other time if you want.

In this procedure, a given pair of acoustic stimuli was in effect for approximately 5 min (320 s). During this period the participant was always exposed to one or the other member of the stimulus pair. The participant controlled which stimulus was heard at any time by means of the two telegraph keys. Every 32 s the acoustic stimulus terminated, and immediately thereafter either the same or the alternative stimulus came on. At the same time the reading lamp mounted on the desk was extinguished for 5 s, during which time the participant was required to make a choice response. Each response initiated a 1 s refractory period during which time further responses were ineffective. The automatic

to choose between. Eight 5-min pairs were presented during each daily hour-long session. A 5-min rest break was given after the fourth pair of sounds. Each experiment involved about 15 daily sessions for each participant. Twelve pairs of stimuli were presented as practice at the beginning of an experiment, but always were excluded from subsequent data analysis.

3. EXPERIMENTS I AND II: PROCEDURE

Experiments I and II were similar except in the degree of knowledge each group of participants had about the source of the sounds that they heard. In both experiments, two samples of corona noise were compared with other environmental and reference sounds, but only in Experiment II had participants been trained to recognize the source of each recording.

Experiments I and II utilized nine of the field recordings; two of these were presented at two sound levels, to yield a total of 11 stimuli. The 11 stimuli, and the unweighted, A-weighted, and D-weighted levels (derived from 1/3-octave band spectra) at which they were presented, are listed in Table I.²

Table I
Scale Values Derived From 1/3-Octave Band Spectra

<u>Spectrum</u>	<u>A-Weighted</u>	<u>D-weighted</u>	<u>Unweighted</u>
Apple Grove Corona	53.9 dB	60.9 dB	55.9 dB
Country	40.9	48.0	51.5
Roanoke Corona	61.7	68.8	62.2
Rain	47.9	55.1	48.9
Air Conditioner	59.1	63.7	64.7
Lawnmower	67.4	73.6	72.5
Trains	77.9	84.1	89.3
Traffic (High)	75.4	79.9	79.2
Traffic (Low)	55.4	59.9	59.2
Octave (High)	80.3	82.5	80.0
Octave (Low)	60.3	62.5	60.0

color photograph representing its source. A brief description of the source (e.g. "CORONA - an electric power line on a rainy day") was given as a caption to each photograph. The names given to the photographs corresponded to the headings in Table I with the exception that the locations of corona recordings were omitted and that the Octave Band was called "Electronic."

During the first two practice days, 25-s samples of the stimuli were presented twice each day. The participants paged through an album containing the photographs in sequence with the sounds. Four different stimulus sequences were employed for training and testing. The participants were instructed to associate each sound with the name of the source given in the corresponding picture caption. After two practice trials, the stimuli were presented again without the photo album, and the participants were tested for recall of the stimulus names. The participants were told their score after each recall test and then presented with four 5-min pairs of stimuli as training in the acoustic menu procedure.

At the beginning of the third day, a recall test was given. If the participant scored 100 percent correct, the final four training pairs (total of 12) for the menu were administered. (Only one participant scored less than 100 percent, but needed only one additional practice trial to achieve 100 percent correct.) The first four pairs for actual data collection in the acoustic menu were then administered to conclude the third day.

The procedure for Experiment II was, in all other respects, identical to Experiment I. After completing the experiment, a final test of recall for the names of the sound sources was given.

4. EXPERIMENTS I AND II: RESULTS

Figure 1 shows the mean proportions of available time (107 min/stimulus for each participant) spent in each stimulus for each group of 26 participants as a function of the sound pressure level of the stimulus. Circles represent the data for Experiment I, squares for Experiment II. The vertical bands drawn through the data points represent plus and minus one standard error of the mean for Experiment I. Standard errors for Experiment II were comparable. Identical, but separate, analyses were conducted on these data for Experiments I and II.

A one-way analysis of variance was performed on the proportions of available time spent in each stimulus, using an arcsine transformation of the proportions for each of the 26 individual participants in each group (Winer, 1962). These analyses disclosed a significant effect of acoustic stimulus, $F(10,250) = 344.30$, $p < 0.001$, $\omega^2 = 0.929$ in Experiment I; and $F(10,250) = 351.44$, $p < 0.001$, $\omega^2 = 0.930$ in Experiment II. As indicated by ω^2 , the type of acoustic stimulus accounted for approximately 93 percent of the variation in the time spent in the various stimuli for both experiments.

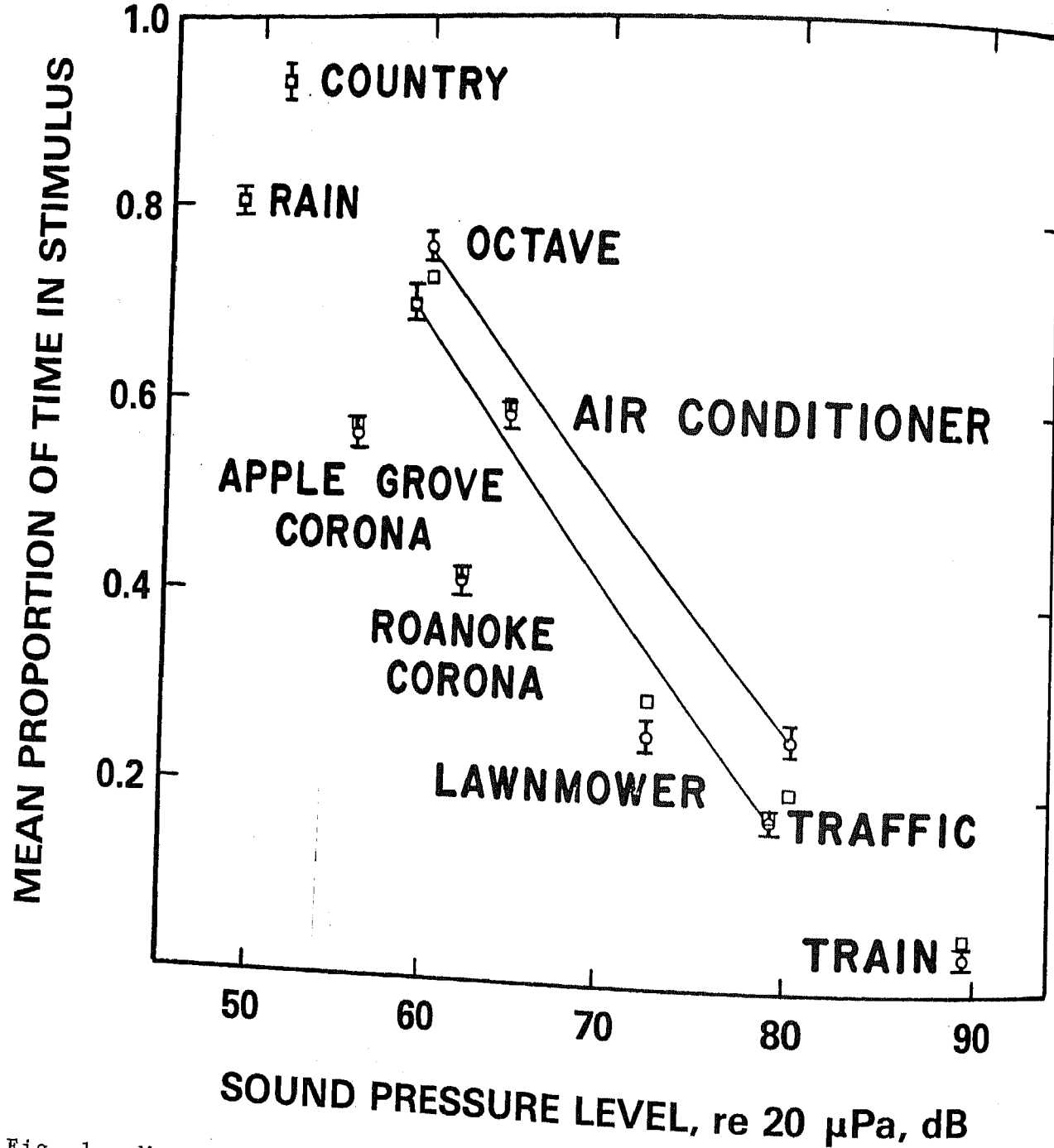


Fig. 1. Mean proportion of the time spent in each stimulus as a function of sound pressure level. Circles represent data from Experiment I, squares from Experiment II. Vertical bars represent one standard error of the mean for Experiment I.

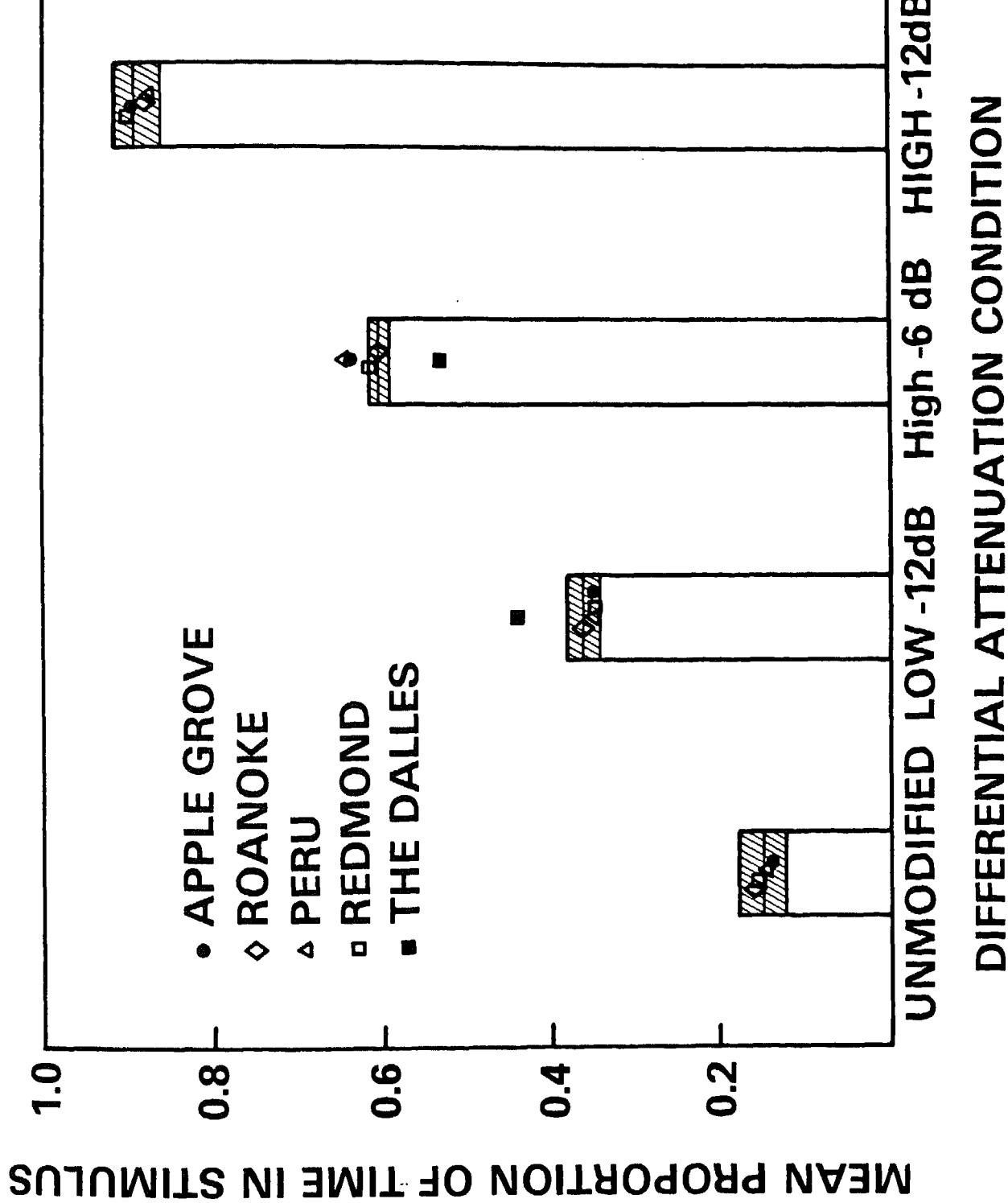


Fig. 2. Mean proportion of the time spent in each stimulus for four differential attenuation conditions. Vertical bars represent data pooled across the five difference corona sample locations (hatched area = \pm one estimated standard error of the pooled mean).

cedure to be the same, the mean time collapsed across stimuli is the same for every participant. Between the two experiments, differences in the preference structures for the acoustic stimuli are only indicated by the stimulus by experiment interaction. Since the interaction of stimulus with experiment was not significant, the preference structure for the stimuli did not vary substantially from one experiment to the other.

With proportion of time spent in a stimulus as a measure of preference for that stimulus, five individual comparisons were selected for post-hoc statistical evaluation. Dunn's (1961) procedure for multiple comparisons revealed the following statistically significant relationships in both experiments: (1) Country was preferred to the Apple Grove Corona sample (participants spent significantly more time in the country sound than in the corona sound); (2) Rain was preferred to the Roanoke Corona sample; (3) Low-level Octave Band was preferred to the Apple Grove Corona sample; (4) Low-level Octave Band was preferred to the Roanoke Corona sample; (5) the Apple Grove Corona sample was preferred to the Roanoke Corona sample.

The sound level of the octave band required to achieve equal preference with the corona stimulus samples was estimated by linear interpolation. An equal preference relationship can be estimated by the sound levels at which listeners would spend equivalent amounts of time in each stimulus when presented with a given pair of acoustic stimuli. In Fig. 1 straight-line segments connect the high- and the low-levels of the Traffic noise and of the Octave Band. The horizontal intersections of the data points for both samples of corona noise with the Octave Band line segment were projected onto the abscissa to estimate the sound pressure level of the octave band that would be equally preferred to each corona sample. In addition, mean proportion of time in the stimulus was plotted as a function of A-weighted and D-weighted sound level (see Table I). The same procedure was followed to estimate the A-weighted and the D-weighted sound levels of the octave band that would be equally preferred to each corona sample. These results indicated that, in order to achieve equal preference with either corona sample, the octave band would have to be presented at a sound pressure level approximately 11 dB higher than the particular corona noise sample. A-weighted sound level increased this difference to about 13 dB, while D-weighted sound level reduced the discrepancy to about 8 dB.

The two corona samples were also compared with the interpolated points along the regression line for the collection of the seven remaining natural stimuli (Octave Band omitted). The mean proportion of time spent in these seven stimuli is well represented by a linear relationship with sound pressure level: $r = -0.97$. In this case a representative environmental sound would have to be presented at a sound pressure level approximately 8 dB higher than the particular corona noise sample in order to yield equal preference. A-weighted sound level reduced this difference to about 3 dB, while D-weighted sound level further reduced the discrepancy to about 2 dB.

cal differences among the stimuli. For the regression of proportion of time on sound level in Experiment I, the correlation coefficients (and standard errors of estimate) for A-weighted, D-weighted, and unweighted sound levels were -0.921 (0.113), -0.964 (0.077), and -0.933 (0.104), respectively. The comparable values for Experiment II were -0.946 (0.092), -0.981 (0.055), and -0.944 (0.094). Although the difference between these correlation coefficients does not appear large, standard error bands, indicating the extent to which values cluster about the regression line, vary by nearly a factor of two. The rank orderings of the various scales must be regarded with caution, however. The commonly used statistical tests of differences between correlation coefficients require that the coefficients be independent (Edwards, 1967). Since the same set of proportions was included in every correlation for the respective experiment, the coefficients are not independent, and thus no formal inferential statistical analysis was attempted.

At the end of Experiment I a brief sample of each stimulus (25-s duration) was presented and a questionnaire was administered to determine whether the participants recognized the various sounds. None of the 26 participants in Experiment I identified either of the corona recordings as transmission line audible noise, although two descriptions of the Apple Grove corona sample referred to an "electric" sound. Corona samples were generally associated with static-like noises ("static," "TV station off the air," etc.) or blowing-like noises (fan, blower, air conditioner, etc.). All 26 participants in Experiment II correctly identified each of the nine test spectra on a similar post-test.

5. EXPERIMENT III: PROCEDURE

Experiment III examined preference for samples of corona noise subjected to various spectral modifications. Either the high or the low frequency portion of the corona noise spectrum was differentially attenuated. In this manner, the relative aversiveness of high and low frequency portions of the spectrum could be compared.

Each of the five samples of corona noise was subjected to four different attenuation conditions. The field recordings were electronically filtered by a matched low-pass, high-pass filter. For each filter, the 3-dB down cutoff frequency was 500 Hz, with skirts of 24 dB/octave. The low-frequency portion (below 500 Hz) and the high-frequency portion (above 500 Hz) of the spectrum were controlled by separate attenuators, and the two portions were summed back together across a summing network (equal weights). Thus the low- and the high-frequency portions of the corona noise spectrum could be differentially attenuated. With both attenuators set at 0 dB insertion loss, the resulting spectrum was essentially unmodified, except for a minor and indiscernible perturbation of phase at the crossover frequency of the filters. These unmodified spectra (0-dB differential attenuation) were all adjusted to produce the same A-weighted sound level of 60 dB in the listening room. They represented five of the 20 stimuli of Experiment III.

situation encountered in evaluating possible engineering modifications to power line design. These three differential attenuation conditions provided an additional 15 stimuli when applied to each of the five corona samples. Thus there was a total of 20 acoustic stimuli-- five samples of corona noise, each presented under four attenuation conditions.

The 80 pairs of stimuli consisted of two types of comparisons: comparisons between attenuation conditions and comparisons between unmodified corona noise samples. Comparisons between the four attenuation conditions were made only within corona noise samples, yielding 12 ordered pairs of stimuli for each of the five corona noise samples. Comparisons between attenuation conditions thus consisted of a total of 60 stimulus pairs. The comparisons between unmodified corona noise samples consisted of all possible pairs of the five spectra, yielding an additional 20 ordered pairs of stimuli.

6. EXPERIMENT III: RESULTS

Figure 2 shows the mean proportions of available time (32.0 min/stimulus for each participant) spent by the group of 25 participants as a function of the differential attenuation condition for each of the five corona noise samples. The height of the line separating the hatched portions of the vertical bars represents the proportion of time spent in a given stimulus averaged over the five corona noise samples under a given attenuation condition. The hatched portions of the bars represent plus and minus one standard error of the mean, averaged from the standard errors for the five corona samples. The 20 standard errors ranged from 0.008 to 0.032, indicating that the variability associated with the acoustic stimuli was relatively small and homogeneous.

Analysis of variance (four by five repeated measures) was performed on the comparisons between attenuation conditions (using an arcsine transformation of the proportions for individual participants). This analysis disclosed a significant effect of attenuation condition, $F(3,72) = 169.30$, $p < 0.001$, $\omega^2 = 0.84$. The attenuation condition strongly influenced the amount of time spent in the acoustic stimuli, accounting for about 84 percent of the variance. Post-hoc comparisons using the Tukey (a) procedure (Winer, 1962) revealed that the means for the four attenuation conditions all differed significantly from one another ($p < 0.05$).

Because attenuation conditions were compared only within corona noise samples, the total amount of time spent in the four conditions combined was constrained by the experimental procedure to be the same for each corona noise sample. Thus, the overall effect of selecting corona noise samples from different locations could not be tested in the statistical analysis for this subset of the data. (Relative preference for different corona samples was obtainable from the comparisons between unmodified spectra described below.) The above analysis of variance also showed a significant interaction between the corona noise spectrum

The mean proportion of available time (42.7 min/stimulus for each participant) spent in each of the five unmodified corona spectra (all adjusted to the same A-weighted level), varied from 20 percent (The Dalles) to 86 percent (Roanoke). A one-way (repeated measures) analysis of variance disclosed a significant effect of corona noise sample, $F(4,96) = 94.06$, $p < 0.001$, $\omega^2 = 0.79$. (As in the previous analysis, an arcsine transform was applied to the proportions for individual participants.) The proportion of variance accounted for by the different unmodified corona samples was large (79 percent) and post-hoc comparisons showed that the means for the five samples were all significantly different from one another ($p < 0.01$).

7. DISCUSSION

The conclusions to be drawn from these experiments are limited by the fact that most of the stimuli were presented as they were recorded out-of-doors, typically at the property right-of-way. Therefore, the sounds reproduced in the listening room represent the worst indoor case, in which a listener is near a large open window. With this restriction in mind, and recognizing the limited number of noise samples employed, several conclusions may be drawn.

Corona noise samples at natural levels (Apple Grove and Roanoke samples) were more aversive than ambient sounds near the line (Country and Rain), even with the noise of rainfall present. Although the sound level of corona is relatively low, corona noise is about as aversive as other environmental sounds which are approximately 8 dB higher in sound pressure level (3 dB in A-weighted level). This relative aversiveness of corona noise cannot be attributed exclusively to people's feelings about power utilities or fear of power lines. Identical preference structures were obtained in Experiments I and II, even though none of the participants in Experiment I knew the source of the corona noise stimuli, while in Experiment II all of the participants knew the source of the noise.

High-frequency (above 500 Hz) portions of the corona noise spectrum contributed more to its aversiveness than low-frequency (below 500 Hz) portions. While 12 dB of low-frequency attenuation did reduce aversiveness, it was less effective than even 6 dB of high-frequency reduction. Thus engineering efforts at corona noise reduction may be optimally directed at high-frequency (hiss and crackle) portions of the noise, at least for outdoor or open-window exposure.

There were meaningful differences in the aversiveness of different corona noise spectra. Two samples at natural levels (Apple Grove and Roanoke) differed significantly from each other in aversiveness; and five corona noise samples, each adjusted to an A-weighted level of 60 dB, all differed significantly from one another. This indicates the need for systematic sampling of transmission line sites and weather conditions for future research.

Of the simple frequency weighting scales used to measure noise, D-weighting appeared most successful. The superiority of D-weighting over A-weighting in accounting for the data of Experiments I and II came almost entirely from

environmental noise measurements. D-weighted sound level is primarily employed for aircraft noise.

Thus the A-weighting scale would appear most appropriate for preliminary assessments, initial surveys, and general applications involving measurements of corona noise. If more precision is required from a simple frequency weighting scale, D-weighted sound level might be preferable. Examples of the latter instance might be evaluating slight alterations of the frequency spectrum as a result of changes in the design of transmission lines, or making relative judgments of environmental impact where a possible difference of ± 1 to 2 dB is important. Of course, the entire interpolation analysis upon which these recommendations are based must be regarded with caution. The differences in discrepancies between A-weighted and D-weighted sound levels are small, and no formal statistical analyses were attempted.

8. NOTES

¹The 1/3-octave band analyses of the field-recorded spectra, as reproduced in the listening room occupied by the participant, will be presented in forthcoming reports.

²Sound level is the frequency-weighted sound pressure level in decibels obtained by applying a standard frequency-weighting function for attenuating part of the sound spectrum. The A-weighting function discriminates against lower frequencies, and to a lesser extent against higher frequencies, according to people's "loudness" judgments at moderate sound levels. The D-weighting function, derived from "perceived noisiness" judgments, is similar to A-weighting but gives greater emphasis to frequencies between 2000 and 5000 Hz. For details of these weighting scales, see K. S. Pearsons and R. L. Bennett, Handbook of Noise Ratings, Rep. CR-2376 (Nat'l Aeronautics & Space Admin., Wash., DC, 1974).

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1. INTRODUCTION

The increasing need for ultra-high-voltage power lines raises the serious question of what effects exposure to high intensity electric fields will have on both human beings and infrahuman species. A preliminary study is underway to develop and thoroughly test the experimental protocols and apparatus which are planned for a major study of the behavioral and biological effects of high intensity 60 Hz electric fields.

The African baboon (Papio anubis and Papio cynocephalus) has been chosen as an animal model for the examination both of individual performance (operant conditioning) and natural (social) behavior. We are especially interested in possible effects on higher integrative functions of the central nervous system. The behavior of baboons is being observed before, during, and after exposure to 60 Hz electric fields at a maximum intensity of 60 kV/m.

Presently, the first group of subjects is being exposed. This paper covers the apparatus, experimental protocols and plans for future studies. The studies will first determine what kinds of effects (if any) occur at a 60 kV/m field intensity and then determine the intensities of exposure at which effects are just barely noticeable.

2. EXPOSURE FACILITY

2.1 High voltage exposure area. An overall view of the exposure area (under construction) is presented in Figure 1. The telephone pole and timber construction will be entirely covered by light-gauge wire mesh which, along with the eight-foot chain-link fence which will surround the area, will provide shielding for personnel and animals outside of the exposure area.

The building just behind the exposure area contains a high voltage control room and an observation room. Figure 2 presents a closer view of the observation room and the steel gratings which will form the floors of the animal's cages. When the perimeter fence is completed, the chain-link wire fabric will extend to frame the observation windows. A lighter-gauge wire mesh will cover the glass to provide shielding for the observers inside the observation room.

The animal cages will be located on the steel grating and the high voltage bus-bar structure will be located approximately two-feet above the tops of the cages. The bus bar and cages will be protected by a fiberglass weather cover.

A 190 kV transformer with a current rating of approximately 25 mA will be used to obtain a maximum field intensity between the high voltage bus-bar

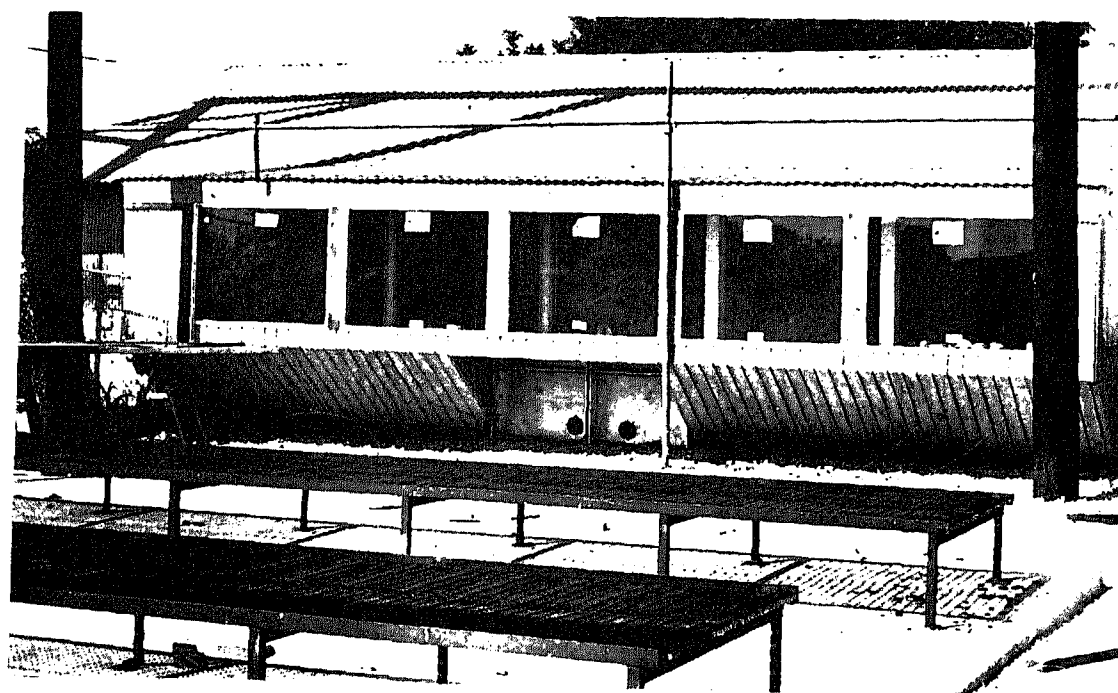
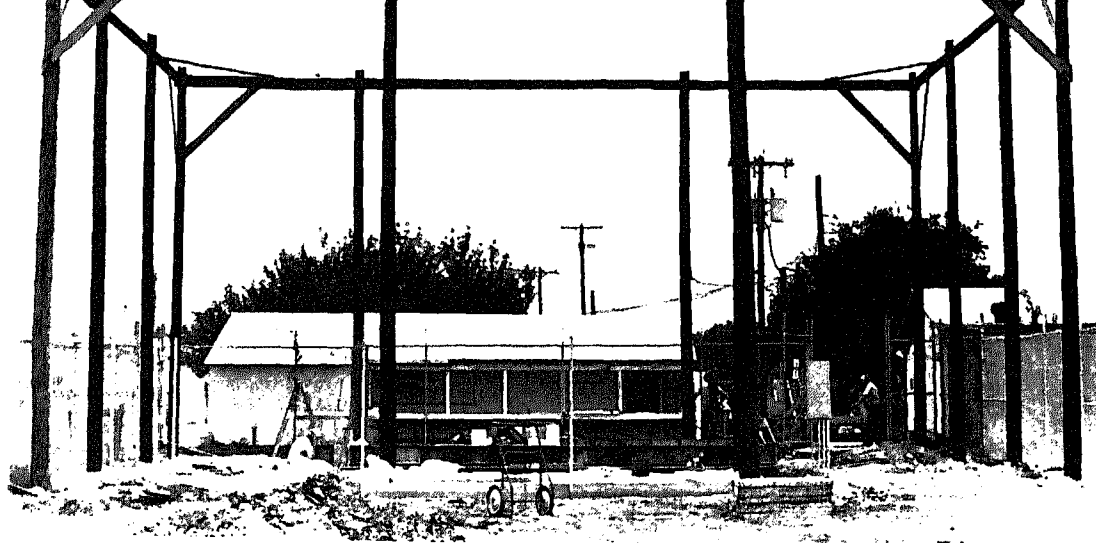


Figure 2. Exposure Facility - Cage Floors and Observation Room

¹Kaune has indicated that there can be problems in providing drinking water to animals while electric fields are on. To alleviate these problems, we have carried out some experiments with the animals to note the minimum height at which they can obtain water from "Lixit" supplies. By maintaining a water supply at a very small height above the true ground, it should be possible to minimize the problem of potential difference between the animal's mouth and the mouth of the water supply tube. Initially, a grounded watering system will be used but it might be necessary to change to a resistance grounded system in order to equalize potentials on the animal and the water tube.

2.2 Cages. One of the individual behavior cages is shown in Figure 3. The cage shell is made of a fiberglass and PVC foam laminate. The shell, which is extremely light and strong, is covered with three coats of a non-toxic epoxy paint. The front grill of the cage is made of hollow square cross-section fiberglass structural members and solid one-inch diameter fiberglass rods. The square opening at the bottom of the front grill is both for transferring the animals in and out of the cage and for the behavioral panel which is described in Section 6.1 below. The cages have been designed with special concern for the need to use materials and construction techniques that will minimize the possibility of "tracking" in order to prevent any degradation in the materials. All materials and construction techniques have been selected to minimize the possibility of moisture intrusion. As a further precaution, the facility will not be operated in wet weather.

2.3 Holding cages for the social behavior subjects. The preliminary holding cages for the social behavior subjects are shown in Figure 4. Each group of four baboons will live in one of the cages prior to being placed in the exposure facility. The social behavior cage in the exposure facility is the same shape and size as the holding cage (23 feet long, four feet deep and four feet high).

Animals are introduced to the holding cage through sliding doors (not shown in Figure 4) at either end of the cage. Partitions can be inserted into the cage dividing it into sections which allow animals to be segregated or allow access through side gates to any desired part of the cage for thorough cleaning.

3. FIELD MEASUREMENT

A relatively small spherical dipole (radius of 1.55") has been built to

¹Kaune, W. T., Phillips, R. D., Hjerlesen, D. L., Richardson, R. L., and Beamer, J. L., A Method for Exposure of Miniature Swine to Vertical 60 Hz Electric Fields. IEEE Transactions on Biomedical Engineering, Vol. BME-25, No. 3, May, 1978. pp. 276-283.

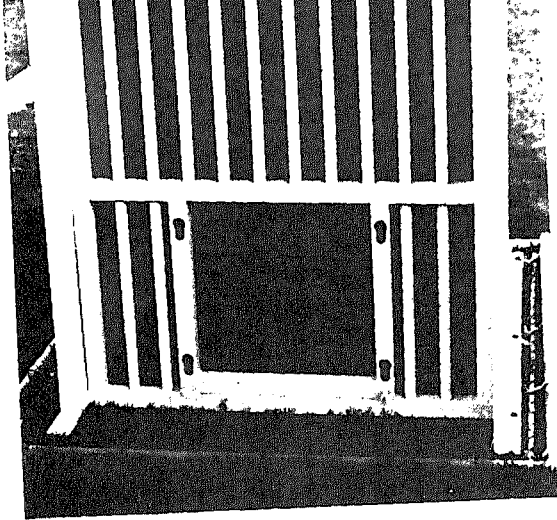


Figure 3. Individual Subject Cage

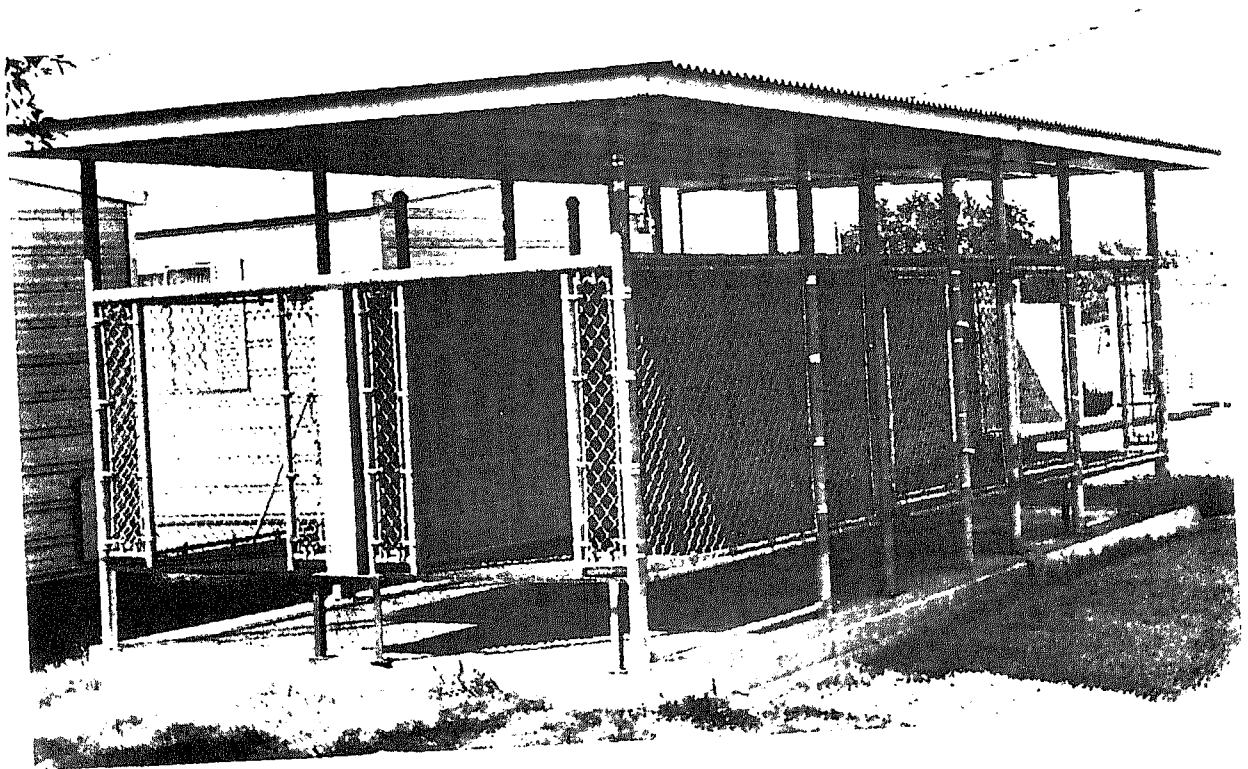


Figure 4. Holding Cages for Social Behavior Subjects

- volume with the consequent elimination of field distortion due to the transmitter electronics package.
- The spherical shape provides the largest radius of curvature which serves to both minimize corona problems in high strength fields and to allow closer mapping of the fields near the baboon subjects without distorting those fields.

A fiber optic cable is used to transmit information from the probe to the receiver-display unit (see Figure 6). Metallic cables would be undesirable since they could perturb the field. Minimal perturbation is produced by a glass cable. The completed probe system mounted on a telescoping fiberglass pole is shown undergoing test in Figure 7.

In the preliminary study, the maximum field strength within an empty cage will be determined as a function of voltage between the high voltage plate and ground. The exposure intensity will be defined as the electric field intensity within an unoccupied cage. Some attempt will be made to determine the effect of an animal on the field intensity in the vicinity of that animal by measuring field intensities close to either an anesthetized baboon or a baboon cadaver placed within the cage.

4. SUBJECTS AND CLINICAL SCREENING

The animal model should be as similar to man as possible because there is a general conviction that results obtained with such an animal are more readily applicable to man. The overall similarity of the nonhuman primate to man is particularly important when one is concerned with the reaction of the entire organism to a stimulus and when one is concerned with the higher integrative functions of the central nervous system. For an investigation of social behavior, a species is needed which exhibits a wide range of social interactions. A species for which the control and channeling of aggression is important is especially desirable since man is clearly such a species.

For this project, a primarily terrestrial subject is needed. In a vertical electric field, a group of arboreal subjects could encounter very unusual stimuli, e.g., shock level currents flowing from an elevated subject to a grounded subject. It is necessary to keep the subjects on or near the ground. For an arboreal subject, this would be a stressful environment. The baboon is a terrestrial primate which is phylogenetically close to man and resembles man both physiologically and behaviorally. The subjects in this study are feral baboons of the varieties that are typically trapped in East Africa, Papio anubis (olive baboon) and Papio cynocephalus (yellow baboon). Two groups of social animals are being used in this preliminary study. The first group consists of two males and two females (ages 2.5 to 3.5 years). Figure 8 is a photograph of one of the first social subjects, a 3.5 year old male. These animals have not yet reached sexual maturity. The second group of social animals has older members, two males and two females (4 to 4.5 years), who have just reached sexual maturity.

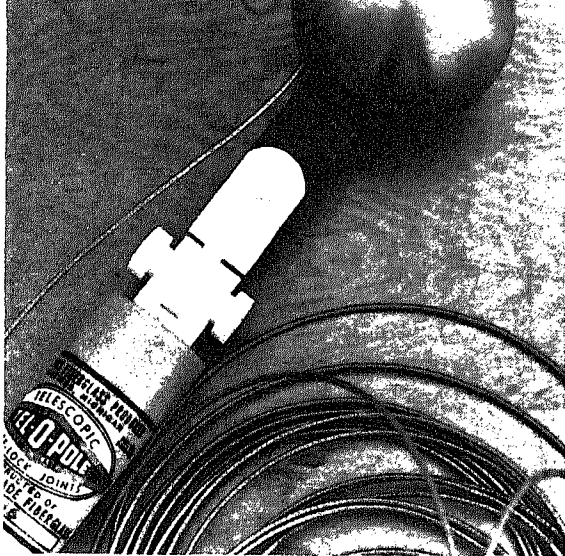


Figure 5. Electric Field Measurement System - Spherical Dipole Probe

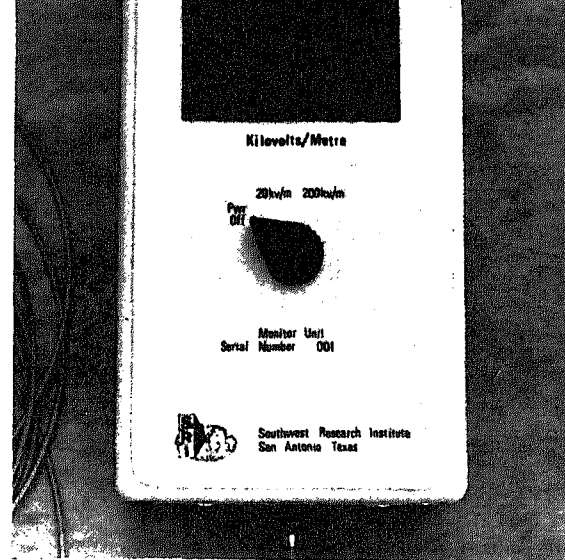


Figure 6. Electric Field Measurement System - Receiver-Display Unit

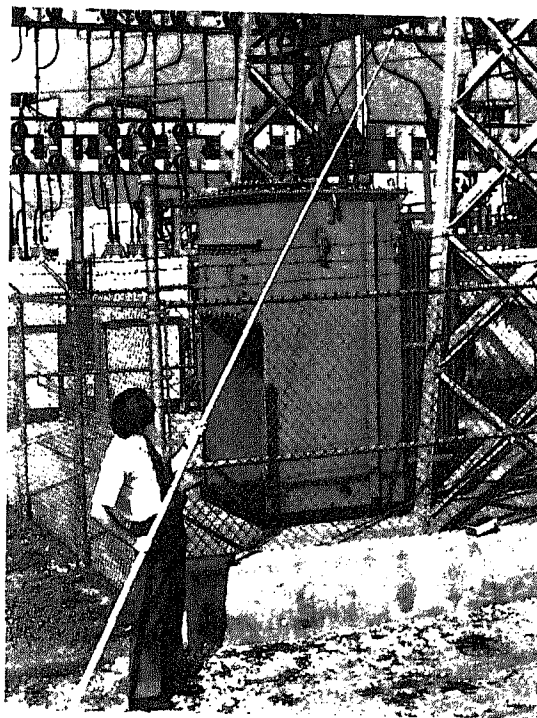


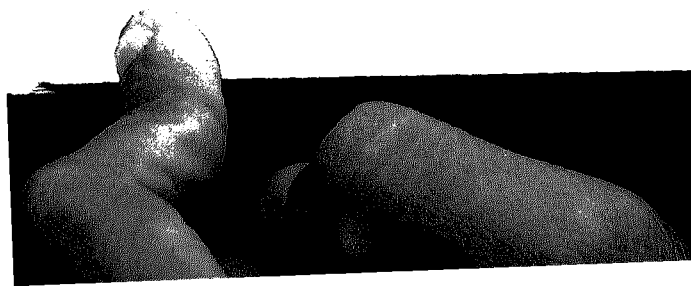
Figure 7. Test of the Electric Field Measurement System



Figure 8. Social Behavior Subject, 3½ year old male, Papio anubis



Figure 9. Individual Behavior Subject, 1 year old male, Papio anubis



high intensity fields in order to insure detection of major organ involvement in disease processes whether related to the field exposure or not. The specific blood and urine tests which are being used are listed in Table 1.

TABLE 1

LABORATORY BLOOD AND URINE TESTS

Hematology

- a. Red blood cell count (RBC)
- b. White blood cell count (WBC)
- c. Differential count with slide
- d. Hemoglobin
- e. Hematocrit
- f. Platelet count
- g. Reticulocyte count
- h. Sedimentation rate

Electrolytes

- a. Sodium
- b. Potassium
- c. Chlorides
- d. Carbon dioxide

Chemical Profile

- a. Calcium
- b. Phosphorus
- c. Fasting glucose
- d. Uric acid
- e. Blood-urea-nitrogen (BUN)
- f. Cholesterol
- g. Total protein
- h. Albumin
- i. Globulin
- j. Alkaline phosphatase
- k. Lactic dehydrogenase (LDH)
- l. Total bilirubin
- m. Glutamic oxaloacetic transaminase (SGOT)
- n. Glutamic pyruvic transaminase (SGPT)

Lipid Profile

- a. Triglycerides
- b. Cholesterol
- c. Lipoprotein electrophoresis

Complete Urinalysis

Hydroxycorticosteroids

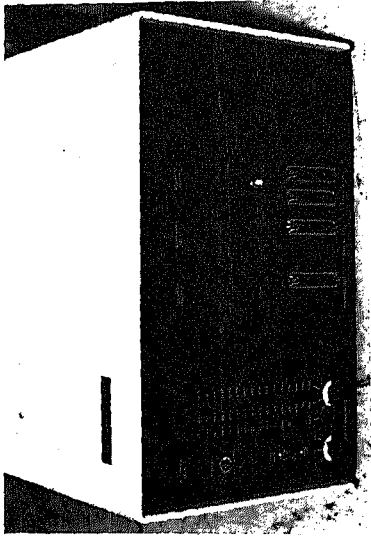


Figure 10. IBM 7406 Device Coupler

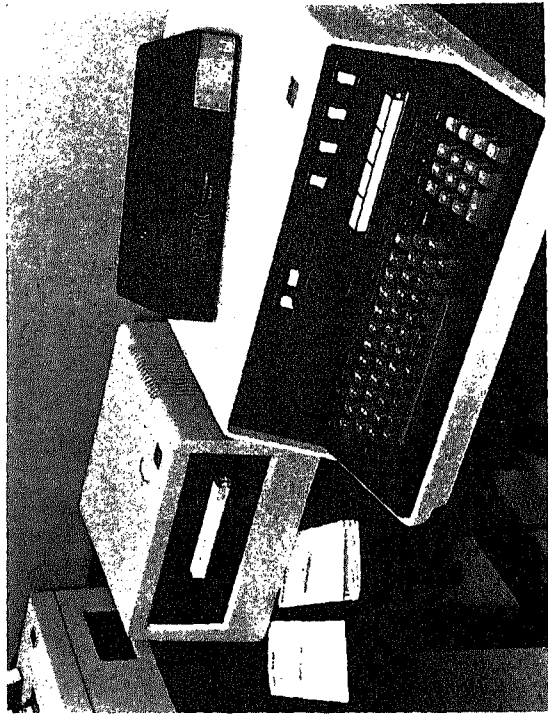


Figure 11. IBM 5110 Computer System

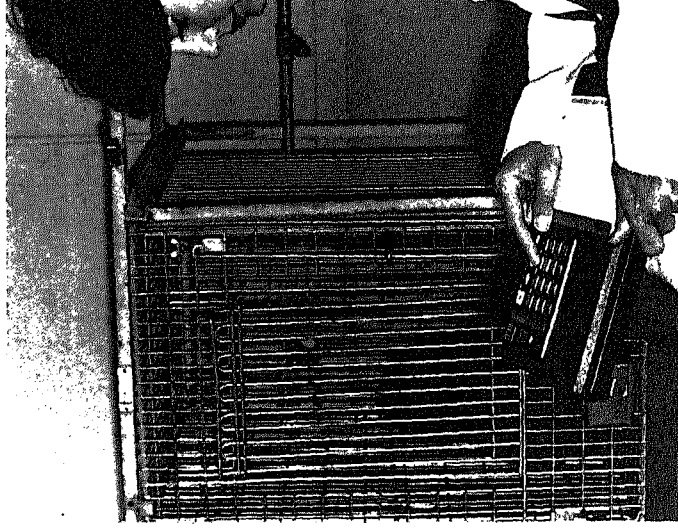


Figure 12. Use of the Data Entry Record Social Behavior

perturbed will have some interaction with the nervous system in a complex organism. In order to be sure that no changes in behavior are overlooked, it is necessary to examine as wide a range of behavior as possible. The techniques now being used to record the natural behavior of a group of baboons essentially tap all of the possible behaviors of these subjects.

5.1 Behavioral units. These units are objectively defined components of the animal's behavior, both as an individual and in relation to other animals around it. The list, which at present includes 186 behavioral units, is intended to be an exhaustive set of behaviors, i.e., at any time a baboon must be doing at least one of these things.

The observers receive extensive training in observation techniques aimed at producing high interobserver reliability. Two observers are employed in this study. Periodically they both observe the same subject at the same time so that reliability checks continue throughout the study.

5.2 Data recording and reduction. The observers use a Datamyte recording device to record their observations (see Figure 12). The Datamyte stores entered numerical (and four alphabetic) codes along with the current count of an internal timer. The device has sufficient memory to hold a full day of observational data.

Observation sessions are directed always at one focal animal and last for ten minutes. At the beginning of a session, the observer enters header data (time, date, focal subject code, observer code, etc.). In each of six hours during an observation day, each animal of the four in the group is observed for one ten-minute session. On days when the high intensity fields are turned on, they are on for four hours of the six hour observation period. The temporal pattern of fields-on and fields-off is varied each day at random and the observers are not told when the fields are on or off. Observations are conducted before an exposure period begins, during an exposure period (both while fields are on and while fields are off) and after the exposure period.

The Datamyte device is connected to an IBM 5110 computer system via it's Serial I/O port (see Figure 11). The computer system includes an auxillary tape drive, a printer and a slave CRT (not shown). The device in Figure 10 is an IBM 7406 Device Coupler which can also be connected to the 5110 computer that is used for the individual behavior studies described in Section 6 below. The Datamyte, when connected to the 5110, can transfer data at 4800 bps (approximately 480 characters per second) so that a completely full Datamyte can be dumped into the computer in about one minute.

The data reduction procedure includes editing records and writing tapes with compact codes. Later, data will be aggregated by subject and behavior code. The basic dependent variables will be frequency (of each behavior unit), duration (of each unit), and an index of first order sequential dependencies (which behaviors follow other behaviors and how often).

were made during the exposure period with fields on and off. These two basic experimental designs (Before - After - Fields-on - Fields-off) will apply to all data analyses including the analyses of individual performance in the operant conditioning tasks.

The dependent variables will be derived from factor analyses of the basic unit behavior data. Factors will be determined for frequency of response, for duration of response and for sequential dependencies observed in the data. The extensive factor analyses necessary to reduce the rather large amount of data to a manageable set of factors will be run on a large host system. All other data manipulations and analyses will be run on the 5110 itself.

After the results of the factor analyses have been determined, a reduced number of variables, i.e., groups composed of similar variables combined into one, can be analyzed. Analyses-of-variance of each of the variables finally selected will allow a determination of behavioral changes as a function of exposure to high intensity electric fields.

6. INDIVIDUAL BEHAVIOR

The studies of individual behavior are modeled after studies which have proven useful in the detection of drug effects and in the general area of behavioral toxicology. In addition, other investigators have found evidence that even low intensity electric fields might effect a performance of primates in operant conditioning tasks.²

There are three different tasks in the present study: a vigilance task, a matching-to-sample task, and a multiple operant schedule (fixed-ratio schedule and differential reinforcement for low response rate schedule). Two members of each group of six juvenile subjects in the preliminary study will be assigned to each task. Two groups of six subjects will be run during the preliminary study.

6.1 Apparatus. Figure 13 shows a behavioral panel from the subject's point of view. This panel is attached to the square opening in the cage grill at the front of the subject's cage. At the top of the panel is a screen on which stimuli are projected from a slide projector. Below the screen are three recessed cylindrical holes, each of which contains a lever that the subject can operate by pulling it forward. Beneath the center lever is a hopper in which banana pellets can be delivered as a reward. The be-

²Gavalas-Medici, R. and Day-Magdaleno, S.R., Extremely low frequency weak electric fields effect scheduled and controlled behavior of monkeys. Nature, 1976, 261: 256-259.

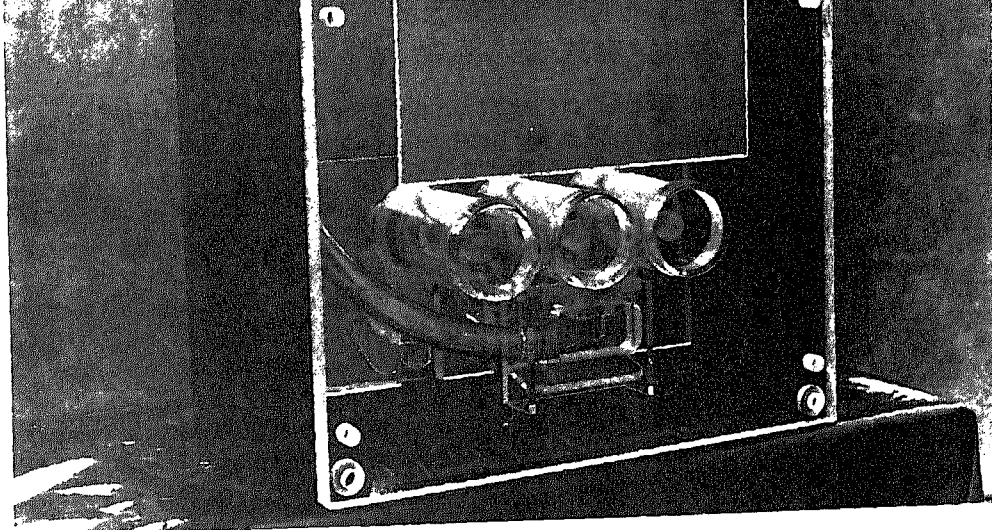


Figure 13. Behavioral Panel - Subject's View

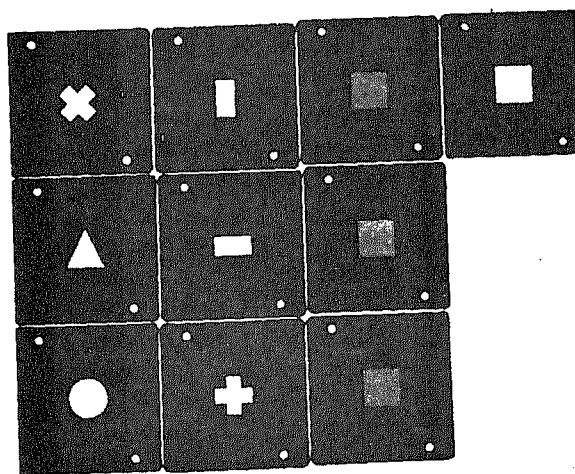


Figure 14. Stimulus Slides - Matching-to-Sample Experiment

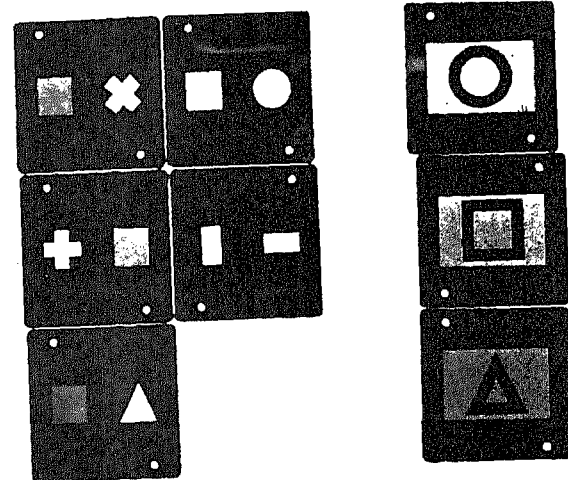


Figure 15. Stimulus Slides - Matching-to-Sample, Vigilance and Multiple Schedule Experiments

the projector being cut off and a termination of the day's run for the subject involved.

6.2 Vigilance. Performance on vigilance tasks are known to be adversely effected by physical stress, fatigue, arousal level, alertness, motivation, and other psychophysiological variables. Although the majority of vigilance studies have been conducted with human subjects, the vigilance paradigm has been successfully employed with nonhuman primates.³

In this task, the subject has one lever which he must operate within a limited period of time following presentation of a "correct" stimulus in order to get a banana pellet reward. Stimuli (any one of three) are presented at approximately five minute intervals. The stimuli used are shown on the right side of Figure 15. These stimuli are not only different geometric shapes but also different highly saturated colors (red, yellow and blue). The dependent variables are response latency and numbers of correct and incorrect responses.

6.3 Multiple operant schedule. Operant performance is examined in a multiple fixed-ratio, differential-reinforcement-of-low-rate (FR-DRL) schedule of reinforcement. Visual cues signal a shift from one reinforcement contingency (FR) to another (DRL). Specifically, the yellow and blue slides on the right side of Figure 15 are used to cue the two operant schedules.

In the FR schedule, the subject is reinforced with banana pellets for every n (e.g., 20) operations of his single lever. In the DRL schedule, the subject is reinforced only if he waits for a specific length of time (after his last reinforcement) to operate his lever again. For both schedules, the distribution of interresponse times is the important datum. In general, the FR schedule is sensitive to any stimuli which change activity levels. The DRL schedule requires that the subject be able to time his responses.

6.4 Matching-to-sample. The matching-to-sample task is concerned primarily with short-term memory. Subjects are first presented with a sample stimulus in the center of the screen. The set of ten sample stimuli are pictured in Figure 14. The square shapes are all highly saturated colors (red, yellow, blue and green). The six non-square shapes (cross, triangle, circle, plus, horizontal bar and vertical bar) are white. When the center stimulus is presented, the subject must operate the center of his three levers. The sample stimulus then goes off for a specific delay after which two stimuli are presented (left and right), one of which is the same as the sample. Examples of pairs of stimuli are shown on the left side of Figure 15. The subject's task is to indicate which stimulus matches the sample by

³De Lorge, J. O., Hess, J., and Clark, F. C., Observing behavior in the squirrel monkey in the situation analogous to human monitoring. Perceptual and Motor Skills, 1967, 25: 745-767.

matched correctly ninety per cent of the time. The dependent variables for this task are latencies, numbers of correct responses, and numbers of errors of each kind, e.g., wrong match, lever presses at the wrong time, wrong lever, etc.

6.5 Scheduling. The individual behavior subjects were first pretrained in a preliminary training laboratory and then placed in the exposure facility at the same time as the social behavior subjects. They are run on the same days (at the same time) that the social animals are observed. In each six hour experimental day, the matching-to-sample subjects and multiple operant schedule subjects are run for one hour each with fields on and a half hour each with fields off. The vigilance subjects are run for two hours each with fields on and one hour each with the fields off. At any time there are two subjects working, one of whom is a vigilance subject.

6.6 Experimental design and data analysis. The experimental design is identical with that of the social behavior study. Comparisons of dependent variables will be made for Before - During - After and Fields-on - Fields-off. Analyses-of-variance will be used for the various comparisons.

7. THE PLANNED MAJOR STUDY

The present study is only a test of the protocols and apparatus which are planned for a major study. The present preliminary study differs from the planned major study as follows:

- Subjects will be used as their own controls. Independent control subjects (never exposed to intense 60 Hz fields) will not be run nor will there be a duplicate exposure facility for the housing and observation of control subjects.
- A smaller number of subjects will be run (20 subjects and 6 spares). The major study calls for 96 subjects.
- Field intensity will not be varied. If any effects are found then dose-response data will be obtained in the major study.
- The exposure facility will be basically an out-door facility, although adequate weather protection will be provided for the subjects' health. The planned major study facility will probably have completely environmentally controlled enclosures for the subjects.
- To avoid deterioration of plastic materials, the high intensity fields will not be turned on during or just after a rainfall.
- In the preliminary study, the biological work will be restricted to the clinical determination of the health of subjects before and after exposure (physical examination, blood, and urine tests). In the major study there will be a more extensive investigation of the immune system.
- The effects of spark-discharge will be investigated in the major study.

Paper not submitted for publication in Proceedings.

1. INTRODUCTION

The rapid growth of power generation and transmission systems in the United States over the last several decades is expected to continue in the future. Due to this growth, people and other life forms may be increasingly exposed to low-frequency electromagnetic fields, raising the question of potentially deleterious effects of such exposure. Of particular concern are the possible biological effects of exposure to 60-Hz electromagnetic fields in the vicinity of existing extra-high-voltage (EHV) and proposed ultra-high-voltage (UHV) transmission lines. Since little reliable data is available to make a risk assessment, and there is a need for a scientifically sound data base to insure public safety and health, research programs were initiated by the Department of Energy and the Electric Power Research Institute to assess the potential biological effects of 60-Hz electromagnetic fields.

As part of the Department of Energy research program, a project was initiated at Pacific Northwest Laboratory in 1976 to investigate the biological effects of 60-Hz electric fields on small laboratory animals. A multidisciplinary research team, consisting of physical and biological scientists, is conducting a broad and comprehensive study to screen for effects of acute and chronic exposure to these fields. This paper comprises a summary of the large amount of data generated from this project during the past two years. Detailed information concerning each major area of research in this project is available in three progress reports⁽¹⁻³⁾ and in published papers.⁽⁴⁻⁹⁾

2. EXPOSURE SYSTEMS

The environment in the vicinity of high-voltage transmission lines is complex and includes many factors that might be sources of biological effects (Table I). For the purpose of controlled laboratory studies we chose to retain only those which dominate in the transmission line environment and which, based on existing literature, have been reported by some laboratories as having produced effects. This decision led to system design criteria which eliminated or minimized all the factors in Table I except the external electric field and the unavoidable consequences of physical interaction between this field and the exposed subject (internal fields and currents; field perception).

¹ Work supported by the U.S. Department of Energy under contract EY-76-C-06-1830.

Primary Field Effects.

Large External Electric Fields

Small Internal Electric Fields

Electric-Field-Induced Body
CurrentsSmall External and Internal
Magnetic FieldsMagnetic-Field-Induced Body
Currents

Field Perception

Hair Stimulation

Other Modes?

Secondary Factors

Spark Discharges

Steady-State Currents

Corona Discharge

Ozone

Audible Noise

Radiofrequency Fields

Hum and Vibration (of significance
mainly in laboratory simulations
of the transmission line fields)Higher-Frequency Harmonics in the
Electric and Magnetic Fields

Three systems were built for exposing small laboratory animals to uniform, vertical, 60-Hz electric fields: a rat exposure system, capable of simultaneously exposing 144 rats individually housed in plastic cages; a mouse exposure system in which 288 mice, 3 per cage, can be exposed simultaneously; and a special test system for experiments requiring direct data acquisition from individual or small numbers of animals during or immediately after exposure. The same numbers of rats and mice are sham exposed under environmental and housing conditions identical to those of the exposed animals. Specifications of the three exposure systems are given in Table II.

One of the four racks used for exposing rats is shown in Figure 1. Each rack consists of four electrodes, with the rats individually housed in plastic cages located on the three lower electrodes. The animals are in electrical contact with a metal mesh floor that forms the top layer of each two-layered electrode. Animal excreta falls through the mesh floor onto absorbent paper in a field-free region on a lower metal plate. The water system is located in this space between the mesh floor and the lower plate, with a small demand-type water nozzle located at the floor level of each cage. This design eliminates possible perturbation of electric field uniformity by the watering system, eliminates shocks to the animals during drinking, and minimizes mouth-to-nozzle steady-state currents during drinking. Pellet food is provided ad libitum in slot hoppers at the front of each cage. The profile of the food delivery system is low to minimize any potential perturbation of field uniformity by the food.

	<u>Rat Exposure System</u>	<u>Mouse Exposure System</u>	<u>Special Test System</u>
Electrode Size (m ²)	1.0 x 2.2	1.0 x 2.2	1.0 x 1.8
Number of Electrodes in Rack	4	5	2
Vertical Separation Between Electrodes (cm)	40	20	*
Number of Racks in System	4	2	1
Size of Animal Cage:			
Floor Area (cm ²)	325	325	*
Roof Height (cm)	10	5	*
Number of Animals per Cage	1	3	*
Maximum Number of Exposed Animals	144	288	*
Maximum Number of Sham-Exposed Animals	144	288	*
Method of High Voltage Energization of Electrodes	Bipolar**	Bipolar**	Monopolar***
Maximum Electric Field Strength Attainable	125 kV/m	150 kV/m	150 kV/m

* Depends on experimental design.

** Adjacent electrodes are energized at the same voltage but of opposite polarity (180° out of phase with each other).

*** The upper electrode is energized and the lower electrode is electrically grounded.

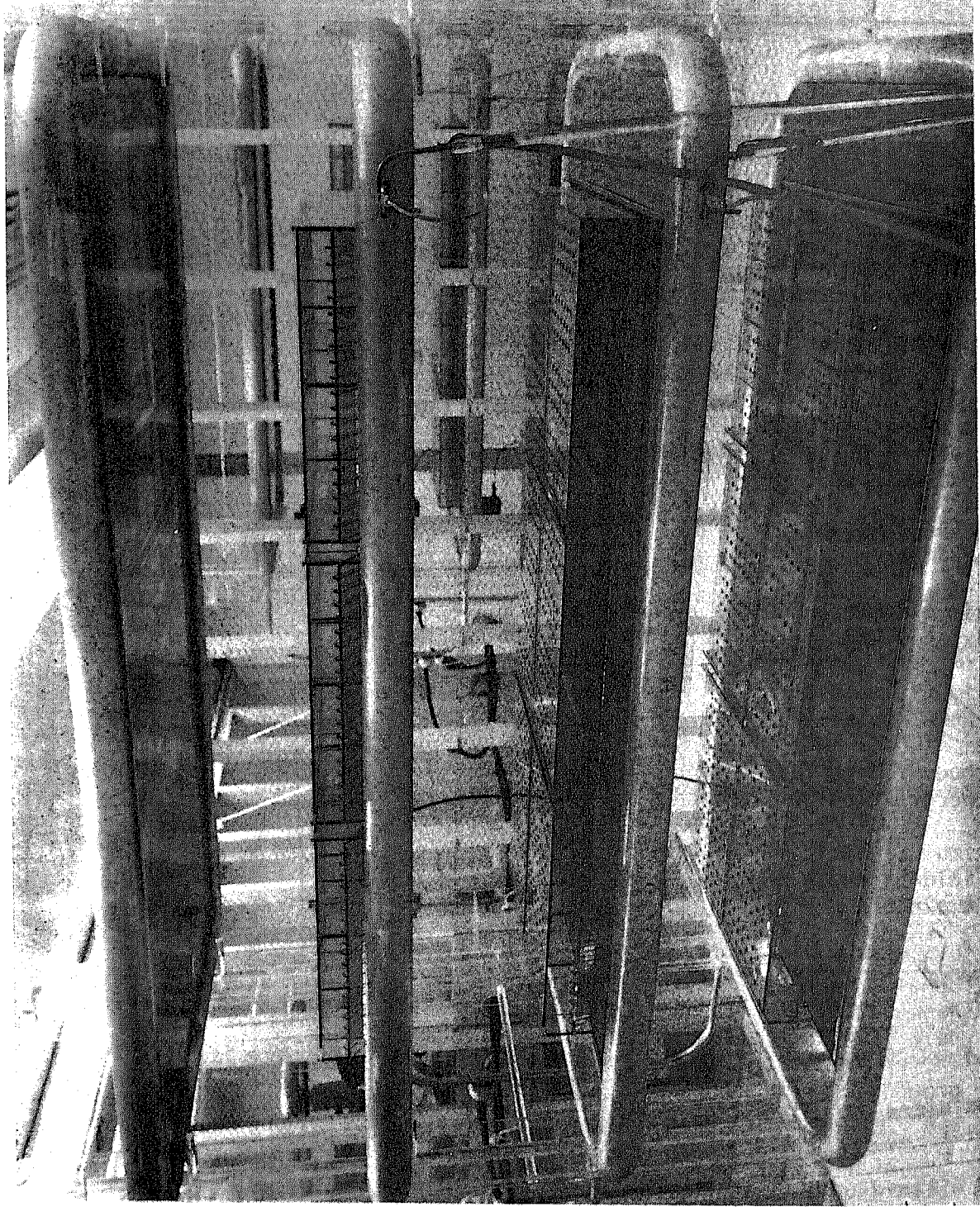


FIGURE 1. System used to house and expose rats to 60-Hz electric fields.

Extensive measurements have been made to characterize the three exposure systems (Table III). Electric field uniformity is $\pm 4\%$ over the total cage area in the rat and mouse exposure systems. The exposure systems are free of detectable levels of audible noise and ozone, and there is very little harmonic distortion. Animals do not receive spark discharges or other shocks from the housing system or from other animals during exposure to electric fields.

TABLE III. Measurements Made to Characterize the Three Systems Used to Expose Small Laboratory Animals to 60-Hz Electric Fields

Parameter	Rat Exposure System	Mouse Exposure System	Special Test System
Electric Field Uniformity over Animal Cage Area (%)	± 4	$< \pm 4^+$	± 7
Audible Noise from High-Voltage System and Electrodes	None	None	None
Ozone Concentration Above Ambient* (ppm)	0**	0**	0**
Total Electric Field Harmonic Distortion (%)	0.3	< 1	0.2
Amplitude of Field-Induced Cage Vibration at 100 kV/m	1 μm @ 60 Hz 0.1 μm @ 120 Hz	< 1 μm @ 60 Hz [†] < 0.1 μm @ 120 Hz [†]	++
Reduction in Total Body Current Due to Shielding from Other Exposed Animals	35%	NM	++

* Background level was 0.02-0.04 ppm

** Measurement resolution was 0.003 ppm

+ Estimated from rat exposure system measurements

++ Depends on experimental design

NM Not measured

3. DOSIMETRY

Considerable care must be exercised in using data derived from animal experiments to predict possible effects on humans in the same situation. This is particularly true in the case of electric fields. In addition to recognizing differences in biological responses between species, the researcher must also be aware of variations in the way differently shaped species will interact physically with the field. This latter factor plays a major role in determining what field strengths are required to reasonably simulate the human situation.

The currents and electric fields induced within the body are a function of body shape, and are quite different for bipeds (such as man) from those for quadrupeds (such as rodents and swine).^(10,11) This is illustrated in Figure 2, which shows a man, a pig and a rat placed in uniform, 60-Hz electric field of 10 kV/m. The strongest surface electric field generally occurs at the top of the body and is enhanced over the uniform field value by a factor of 15-20 for man,⁽¹²⁾ 7 for a pig^(11,13) and about 4 for the rat.⁽³⁾ Estimated current densities are shown at two locations within each body, trunk and lower limbs, and illustrate the strong dependence on body shape. The total current between each body and ground, the short-circuit current (I_{sc}), is also shown. Based on these data, a much higher unperturbed field would have to be used with rats to produce surface fields and internal current densities comparable to those in a man exposed to 10 kV/m. Scaling factors between rat and man are: enhancement, $\sim 4:1$; average trunk current density, $\sim 15:1$; average current density in the lower limbs, $\sim 5:1$.

We selected 100 kV/m for the rat and mouse exposures in the initial biological screening experiments. Due to mutual shielding among exposed animals, this value is reduced to 65 kV/m for the singly housed rats (Table III) and by an unknown and variable factor for the multiply housed mice. Assuming a scaling factor between rat and man of 4-15:1, 65 kV/m for rats would be equivalent to approximately 4-15 kV/m for man.

4. BIOLOGY STUDIES

Experiments are being conducted in 11 major biological areas to screen for effects over a wide range of parameters in rats and mice exposed to 60-Hz electric fields for up to 120 days. Experiments in each major area use separate animal groups and are directed by professionals with specialties in the areas under investigation.

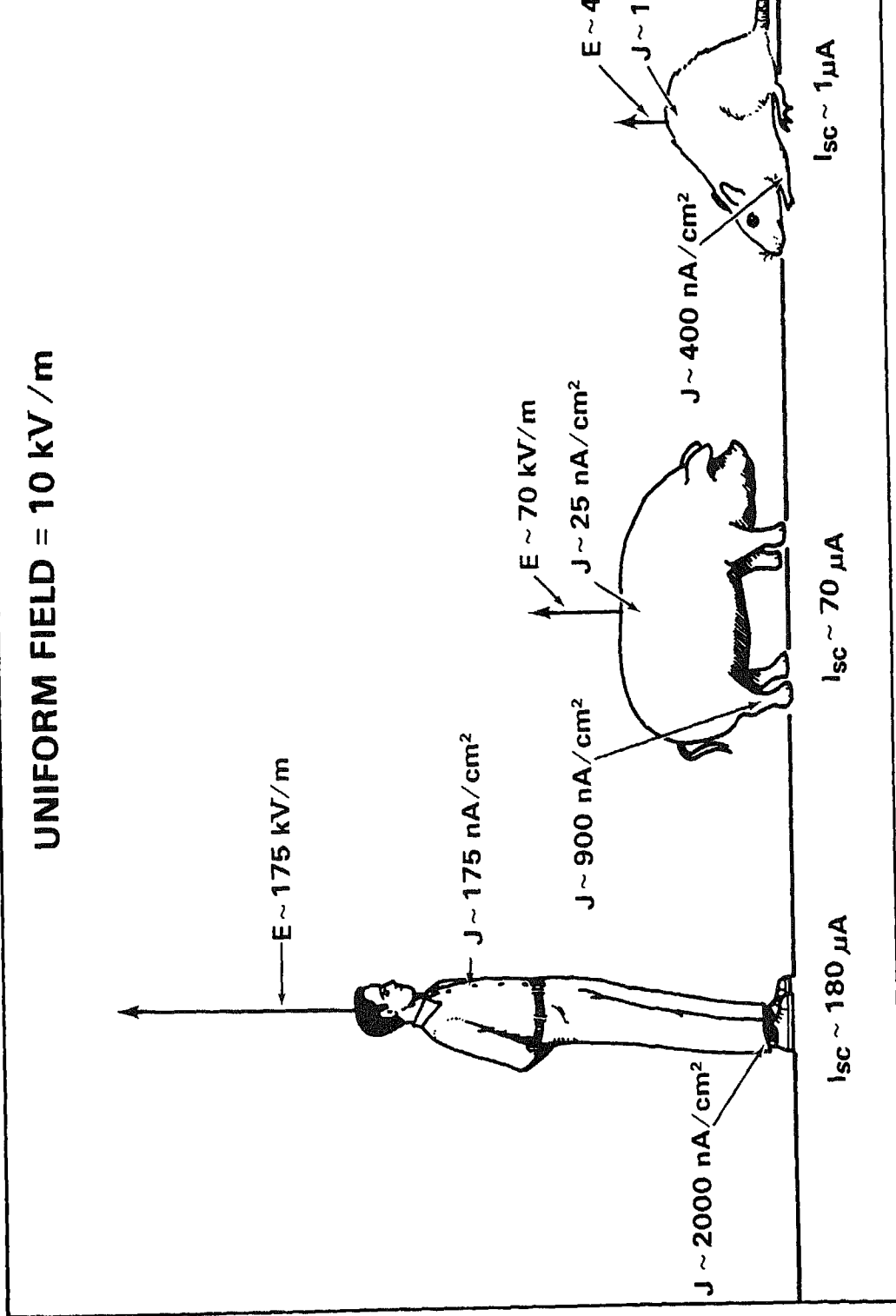


FIGURE 2. Interaction of man, pig and rat with a uniform, 10-kV/m electric field. E represents enhanced field strength at the highest point on the surface of the subject; J is the sectional current density at the trunks and lower limbs of the subjects; I_{sc} is the circuit current between the subject and ground.

mice. All animals received from one supplier are carefully examined before being used in experiments to assure that they are healthy. A sample population from each shipment is sacrificed at delivery for virology screening and histopathologic examination. The remaining animals are maintained in standard cages in an isolation room for 1-3 weeks, ear-coded, then acclimated for 14 days in cages identical to those used in the electric field exposure systems. During exposure or sham exposure, the environment, housing and husbandry are identical for both groups of animals except for the presence or absence of the electric field. This design reduces the risk of obtaining false positive results and increases the ability to detect subtle effects of exposure. In addition, animals maintained in standard cages ("cage controls") are used in many of the experiments to verify that the exposure cages do not produce effects that might mask subtle effects of exposure.

In most of the experiments the animals are about 60 days of age at the start of exposure. Except for several cardiovascular and behavioral experiments, the field strength used for all exposures is 100 kV/m. The exposure period is about 21 hours/day; this allows about 3 hours/day for scheduled measurements, cage cleaning, feeding and watering.

With few exceptions, experiments are double-blind: the principal investigator is unaware of which animals are exposed and which animals are sham exposed until the measurements have been completed. Most experiments are replicated to insure that the results of a single experiment are not due to some unidentified systematic error in that experiment, or to statistical chance. Our statistical criterion for positive effects is $p < 0.05$.

The results of the biological experiments that have been completed to date are summarized below.

Metabolic Status and Growth - R. D. Phillips, Principal Investigator

In six separate experiments, body and organ weights were determined in juvenile (age, 26 days) and young adult (age, 56 days) male and female rats, and in young adult (age, 60 days) male and female mice that were exposed or sham exposed to 60-Hz electric fields at 100 kV/m for 30 days (~ 630 hours). In addition, food and water consumption was measured daily during the 30-day exposure period. In other experiments, a number of parameters related to metabolism and growth were measured in rats that had been exposed to 100 kV/m for 30 days, including: oxygen consumption and carbon dioxide production rates; metabolic rates; circulating concentrations of thyroxine, thyroid-stimulating hormone and growth hormone; lipid, protein, and glycogen levels in liver; and serum concentrations of glucose, urea nitrogen and triglycerides.

There were no reproducible, significant differences between exposed and sham-exposed animals in any of the parameters measured in any of the experiments. These experiments failed to confirm effects reported by other investigators:

Bone Growth and Structure - B. J. McClanahan, Principal Investigator

Bone growth and structure were assessed in juvenile male and female rats that were exposed to 100 kV/m for 30 days starting at 28 days of age. To differentiate any possible direct effect of exposure on bone growth from that of an indirect effect on the general growth pattern of the animals, body weights, kidney weights and liver composition (fat, glycogen, protein and moisture) also were determined.

Exposure had no effect on growth rate of the tibia, morphology of lumbar vertebrae or the tibia, or on cortical bone area and marrow space areas of the tibia. No alterations in the general growth pattern were observed.

Reproduction, Growth and Development - M. R. Sikov, Principal Investigator

A series of three replicated experiments were undertaken to determine the effects of exposure to 60-Hz electric fields at 100 kV/m on reproduction and on fetal postnatal growth and development in the rat.

In the first experiment, a 6-day exposure prior to and during mating did not affect the reproductive performance of either males or females. Continued exposure of the mated females through 20 days of gestation did not affect the viability, size, or morphology of the fetuses. A similar 30-day exposure of the males and of the unmated females did not affect their mating performance or fertility on subsequent testing.

In the second experiment, exposure of the pregnant rat was begun on day 0 of gestation and continued until the resulting offspring reached 8 days of age. There were no differences between exposed and sham-exposed groups in litter sizes or survival of offspring. Body weights and subsequent growth through 42 days of age were the same for both groups. The only differences observed between exposed and sham-exposed animals were in tests of neuromuscular and neurological development through 42 days of age. A higher percentage of exposed offspring showed motile behaviors (moving, grooming and standing) and a lower percentage exhibited righting reflexes at 14 days of age. The results of the two groups were indistinguishable upon retesting at 21 days of age. Tests of the reproductive integrity of the offspring have not disclosed any deficits.

The third experiment also involved a 30-day exposure, beginning at 17 days of gestation and continuing through 25 days of postnatal life. There were no significant alterations in growth or development of the offspring.

Hematology and Serum Chemistry - H. A. Ragan, Principal Investigator

Clinical pathologic evaluations were made in female rats exposed to 60-Hz electric fields at 100 kV/m for 15, 30, 60 and 120 days, and in female mice

count, mean corpuscular volume, reticulocyte concentration, platelet distribution of leukocyte cell types, red cell osmotic fragility, pro-concentrations, bone marrow cellularity, red cell osmotic fragility, pro-thrombin time and iron uptake from plasma. Serum chemistry parameters measured included urea nitrogen, alkaline phosphatase, glutamic oxaloacetic transaminase, glucose, triglycerides, iron, total iron-binding capacity, total proteins, and protein fractions as determined by electrophoresis.

Exposure of rats and mice to 100 kV/m for 15-120 days did not cause reproducible changes in any of the hematologic or serum chemistry parameters assayed. In some cases statistically significant differences were found among exposed, sham-exposed and cage-control animals, but these differences were never consistent across replicates, and did not fit any known biological pattern. It was concluded that these differences were the result of statistical chance and were not due to effects of electric field exposure.

Several investigators have reported effects of electric-field exposure on hematologic and serum chemistry parameters.(14-20) The failure of this study to substantiate these reported effects may be explained by one or more of the following: 1) our exposure systems and conditions are very well defined, and eliminate secondary influences of the electric field, such as spark discharges, ozone, and noise; 2) our exposures have been replicated for each time period, whereas most other studies reporting effects have not been replicated; 3) our sham-exposed animals are more valid controls than "cage-controls" used in some other studies; and 4) our electric field strengths and durations of exposure were, in many cases, different from those used by other investigators.

Immunology - J. E. Morris, Principal Investigator

A series of experiments were conducted to quantitatively assess humoral and cellular components of the immune system. Serum immunoglobulin levels¹ were measured in rats exposed to 100 kV/m for 15 or 30 days and in mice exposed to 100 kV/m for 30³ or 80 days. Complement activity² and peripheral blood T- and B-lymphocytes³ were measured in mice exposed to 100 kV/m for 30 and 60 days. No significant differences were observed between exposed and sham-exposed rats or mice in any of the parameters measured.

In the second phase of this study, we assessed functional immune responses by measuring serum antibody levels in response to a specific antigen and by in vivo assays of cell-mediated immunity. To assess the primary immune response, the serum antibody levels⁴ were measured in mice exposed to 100 kV/m

¹ Competitive binding, double-antibody radioimmune assay.

² Standardized hemolysin assay.

³ Fluorescent-antibody labeling assay (B-cells); spontaneous rosette assay (T-cells).

⁴ Direct-binding radioimmune assay.

cell-mediated immunity was evaluated in mice after 30 days of exposure to 100 kV/m by determining the delayed hypersensitivity to KLH and the contact sensitivity to dinitrofluorobenzene (DNFB). Exposure had no effect on the response of sensitized mice to DNFB. In exposed mice, however, there was a significantly ($p < 0.001$) reduced response to KLH as measured by skin thickness at the site of injection. The mean reaction diameters for the two groups were not significantly different. A replicate of this experiment produced a decreased response to KLH in exposed animals (as measured by skin thickness), but this time the difference between exposed and sham-exposed animals was not significant at the 0.05 level. Another experiment is in progress in which cell-mediated immunity will be tested in mice exposed for 120 days. In addition, in vitro experiments have been initiated to assess this potential effect of electric field exposure on cell-mediated immunity in mice by examining the response of lymphocytes stimulated with mitogens.

Endocrinology - M. F. Free, Principal Investigator

Plasma thyroxine and adrenocortical steroids, and endocrine gland and reproductive tract weights were examined in rats after exposure to a 60-Hz electric field at 100 kV/m for 30 days. In addition, a detailed examination was made of male reproductive endocrinology. This included plasma gonadotrophin levels, plasma testosterone, testicular vein androgens, blood flow rate through the reproductive tract and androgen secretion rates.

Exposure of rats to electric fields had no effect on body weight, weights of endocrine organs or plasma levels of adrenocortical steroids, thyroxine, testosterone or luteinizing hormone. A possible elevation of plasma follicle-stimulating hormone needs to be investigated further, but testicular weights were unaffected by the treatment. In-depth evaluation of the male reproductive system indicates that exposure to 60-Hz electric fields had no effect on testicular blood flow rates, androgen levels, or testosterone secretion rate.

These data are in conflict with previous studies,^(14,19) where much lower field strengths were employed, and suggest that secondary factors (electrical discharges, corona and ozone) may have had a major influence on those experiments. Our results are in general agreement with those of the Italian (ENEL) studies summarized by Cerretelli and Malaguti,⁽²¹⁾ where field strengths of 80-100 kV/m were used.

Cardiovascular Function - D. I. Hilton and R. D. Phillips, Principal Investigators

A series of experiments were conducted to determine whether exposure to 60-Hz electric fields alters cardiovascular function in the rat. Parameters assessed included electrocardiograms (ECG), heart rate, blood pressure and vascular reactivity. In addition, the cardiovascular and endocrine responses of rats to acute cold stress were determined in animals that had been exposed to 60-Hz electric fields.

consisted of measuring the durations of the cardiac cycle. Recordings were made during the first hour after the completion of electric field exposure. No differences were seen between exposed and sham-exposed animals in any of the experiments. These results failed to confirm the findings of Bianchi et al., (22) who reported that exposure of rats to 100 kV/m slowed electrical conduction in the heart.

Systolic, diastolic, pulse and mean systemic blood pressures, and vascular reactivity were measured in rats that had been exposed to 100 kV/m for 35 days. Vascular reactivity was quantitated by measuring the change in pulse pressure in response to an injected dose of phenylephrine, a vaso-constrictor that produces an elevated pulse pressure by increasing peripheral resistance to blood flow. No significant differences were observed between exposed and sham-exposed animals in any of the measures.

Cardiovascular and endocrine responses to cold stress were measured in rats that had been exposed or sham exposed to 100 kV/m for 30 days. Plasma corticosterone and thyroid-stimulating hormone levels were determined in the animals prior to and after being subjected to acute cold stress ($-13^{\circ} \pm 1^{\circ}\text{C}$) for 1 hour. No significant differences were found between exposed and sham-exposed rats before or after cold stress. In a parallel experiment, heart rate, skin temperature and deep colonic temperature were measured during cold exposure in rats that had been exposed or sham-exposed to 100 kV/m for 30 days. Values of both groups were essentially identical.

Pathology - G. M. Zwicker and R. A. Renne, Principal Investigators

Complete necropsy and histopathologic examination of approximately 30 selected tissues per animal were performed on groups of male rats and both male and female mice exposed or sham exposed to a 60-Hz, 100-kV/m electric field for 30 days. Animals were weighed after sacrifice, and selected organs from each animal were weighed. No histopathologic effects of exposure were observed in rats or mice. Exposure had no significant effect on body or organ weights.

Similar gross and microscopic evaluations were carried out on male rats and on male and female mice exposed or sham exposed to a 60-Hz, 100-kV/m electric field for 120 days. Histopathologic survey of the mice revealed no apparent effect of exposure to the electric field. Histopathologic evaluation of rat tissues is in progress.

The results of these studies fail to confirm a report by Soviet scientists (19) that exposure of rats to electric fields at 5 kV/m produces vascular damage and atrophic changes in brain and liver.

Central Nervous System - J. C. Hampton, Principal Investigator

A detailed histologic examination was made of the brains of mice exposed to 100 kV/m for 30 days. Results failed to reveal any differences between exposed and sham-exposed mice.

in a temperature-controlled chamber ($37.5 \pm 0.4^{\circ}\text{C}$) and continuously superfused with a modified mammalian Ringer's solution equilibrated with 95% O_2 and 5% CO_2 . Several parameters and tests were used to characterize synaptic transmission and peripheral nerve function: 1) characteristics of the post-synaptic or whole-nerve compound action potential (including amplitude, area, configuration, rate of rise, and rate of fall); 2) conduction velocity of the postsynaptic or whole-nerve compound action potential, measured at the beginning of the compound action potential (inflection conduction velocity) and at the peak of the compound action potential (peak conduction velocity); 3) absolute and relative refractory periods; 4) accommodation; 5) stimulus strength-duration relationships; 6) changes in poststimulus excitability (e.g., conditioning-test response); 7) frequency response; 8) post-tetanic response; 9) high-frequency-induced fatigue.

Significant differences between exposed and sham-exposed animals were observed among some of the parameters used to characterize synaptic transmission and peripheral nerve function. For synaptic transmission, the rate of fatigue during high-frequency stimulation was less ($p = 0.038$) in exposed animals than in sham-exposed animals. Although not statistically significant ($p = 0.08$), the conditioning-test response curve for exposed animals was shifted in a direction suggesting increased synaptic excitability. Experiments on peripheral nerves demonstrated that conduction velocity in unmyelinated (vagal C) fibers was significantly increased ($+10\%$, $p < 0.01$) following electric field exposure, while there was no detectable effect on myelinated (sciatic A) fibers. Replicate experiments are in progress to confirm these findings.

Most parameters failed to reveal any significant neurophysiological effect of electric field exposure. For those parameters in which there were significant or suggestive differences, the differences are consistent with the hypothesis that chronic exposure to electric fields increases neuronal excitability. The apparent specificity of the effect for unmyelinated nerve fibers is of additional interest because this may lead to knowledge of mechanism(s) and site(s) of action.

Behavior - D. L. Hjeresen, Principal Investigator

A series of experiments were conducted to assess the effects of various levels of 60-Hz electric fields on the behavior of rats. These experiments have focused on perception and passive avoidance behavior, activity during exposure, and performance of a learning task immediately after exposure.

In the passive avoidance experiments, rats were given the option of being exposed to or shielded from various field strengths during short- (45-minute) and longer-duration (~ 24 -hour) tests. Rats were placed in a shuttlebox (Figure 3), one end of which was shielded and the other end visually identical but unshielded from the 60-Hz electric field, and scored for activity (number of end-to-end traverses) and time spent in each end of the shuttlebox.

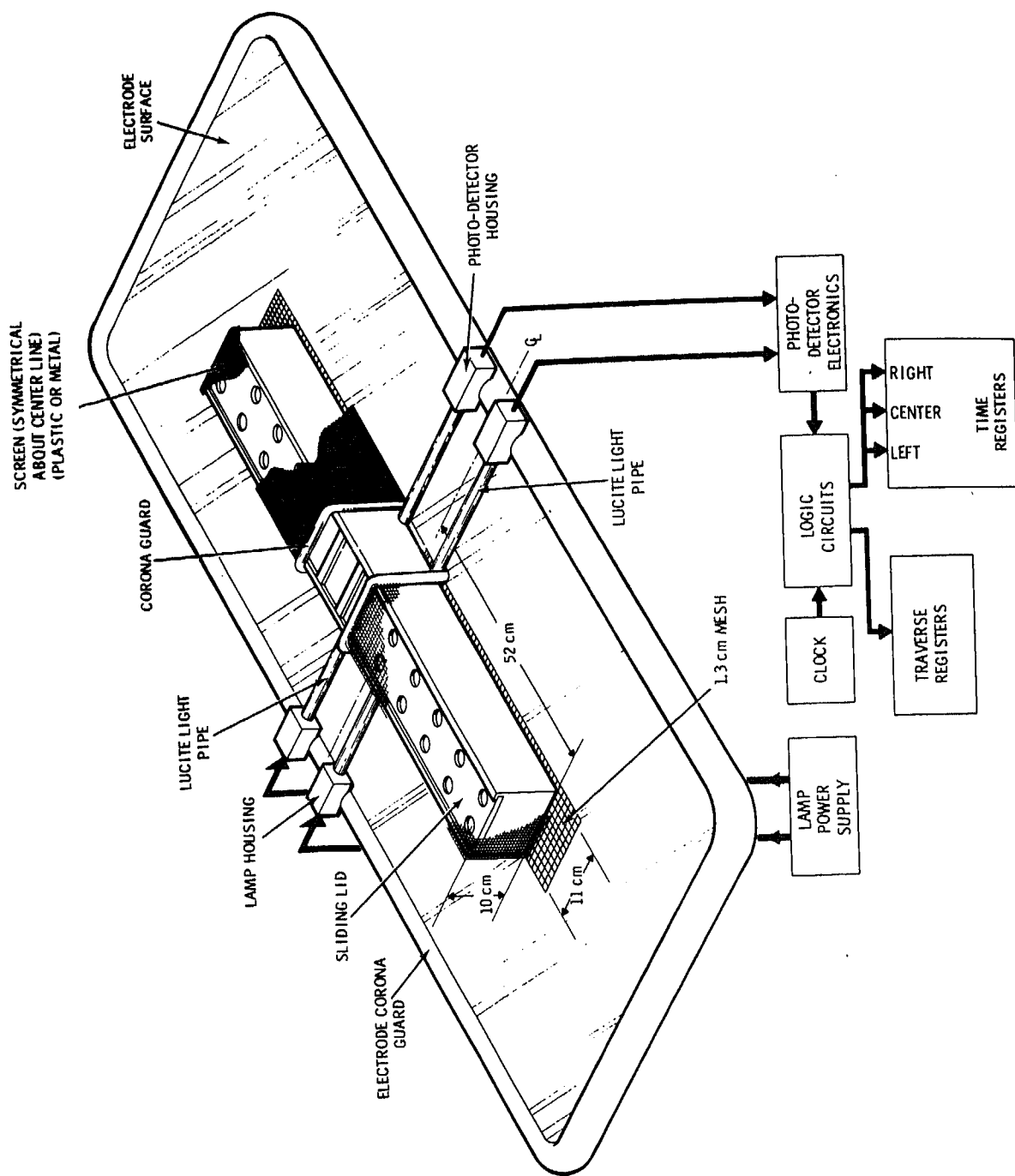


FIGURE 3. Shuttlebox used for behavioral experiments.

this behavioral response.

Activity during the 45-minute tests was significantly greater in exposed rats than in sham-exposed controls. This higher activity was seen at field strengths as low as 50 kV/m and increased with repeated tests.

In longer-duration tests (~ 24 hours, 12 hours light:12 hours dark), rats exposed at 75 or 100 kV/m spent more time in the shielded end of the shuttle-box than did controls during both the light and dark periods. However, rats exposed at 50 kV/m spent more time in the field than controls, but only during the 12-hour light period.

The results of the longer-duration tests confirmed the results of the 45-minute tests in which exposed rats showed an increased activity. This effect was observed in rats exposed to fields as low as 25 kV/m and occurred only during the first hour of exposure.

An experiment was conducted to assess the performance of rats in a learning task after exposure to 60-Hz electric fields at 0, 50 or 100 kV/m for 23.5 hours. After exposure, each rat was placed in a two-compartment shuttle-box and learned to move from one compartment to the other in response to an 80-dB tone in order to avoid a 20-second shock to the feet (an avoidance response). If no avoidance response was made by the rat, it could escape the ongoing shock by moving to the other compartment (escape response). Exposed animals made significantly more avoidance responses than did sham-exposed controls. Also, the average latency to make an avoidance response was significantly shorter in exposed rats than in controls. However, exposed rats made significantly fewer escape responses than did controls, with fewer escape responses by rats exposed at 100 kV/m than by rats exposed at 50 kV/m. The results of this behavioral experiment are consistent with the results of the neurophysiology experiments: exposure to 60-Hz electric fields may increase nervous system excitability.

5. SUMMARY

Exposure of rats and mice to 60-Hz electric fields at 100 kV/m for up to 120 days had no statistically significant, reproducible effects on a number of measures of metabolic status and growth, bone growth and structure, reproduction, hematology and serum chemistry, endocrinology, cardiovascular function, or organ and tissue morphology. A possible effect on cell-mediated immunity was detected and is being evaluated further by examining the response of lymphocytes stimulated with mitogens. Exposure of rats in utero (day 0 of gestation to 8 days of age) had a transient effect at 14 days of age on motile behavior and development of the righting reflex. Significant effects were observed in the neurophysiology and behavioral studies. Exposure to

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1. INTRODUCTION

The U.S. Department of Energy (DOE) is responsible for the Research, Development, and Demonstration (RD&D) of emerging energy technologies and the promotion of energy conservation. A major thrust of the Division of Energy Storage Systems (STOR) of DOE is to stimulate the development and use of commercial energy storage systems throughout the United States. Potential markets for energy storage technologies are found in transportation, building heating and cooling, industrial processes, and utilities. An integral and important part of the planning and evaluation of these projects includes the balancing of energy goals with the environmental requirements to protect and enhance the general health, safety, and welfare of the nation. This means that environmental effects must be considered and potential mitigating measures must be investigated throughout the entire planning process.

The distribution of funding related to environmental control for conservation programs during FY 1977 is shown in Figure 1 (1). Energy Storage Systems received a significant share of the funds to ensure that commercialization of energy conservation projects would not be hindered as a result of environmental problems. This effort resulted in a direct flow of environmentally-related information into the evaluation and planning of each energy storage system.

The broad range of energy storage technologies is shown in Figure 2. Three types of energy to be stored are heat, electricity, and mechanical energy. Sources of these energy types are shown at the left of the diagram, and include solar energy, hydroelectric power, waste heat from power plants, and industrial processes. The storage technologies appropriate to each energy source are shown in the center of the figure. For example, electricity produced by hydroelectric, nuclear, or fossil fuel power plants, can be stored using electrochemical storage, mechanical storage, or thermal storage. Three major end uses for stored energy --

**TOTAL CONSERVATION FY 1977 FUNDING
RELATED TO ENVIRONMENTAL CONTROL: \$5,984,000**

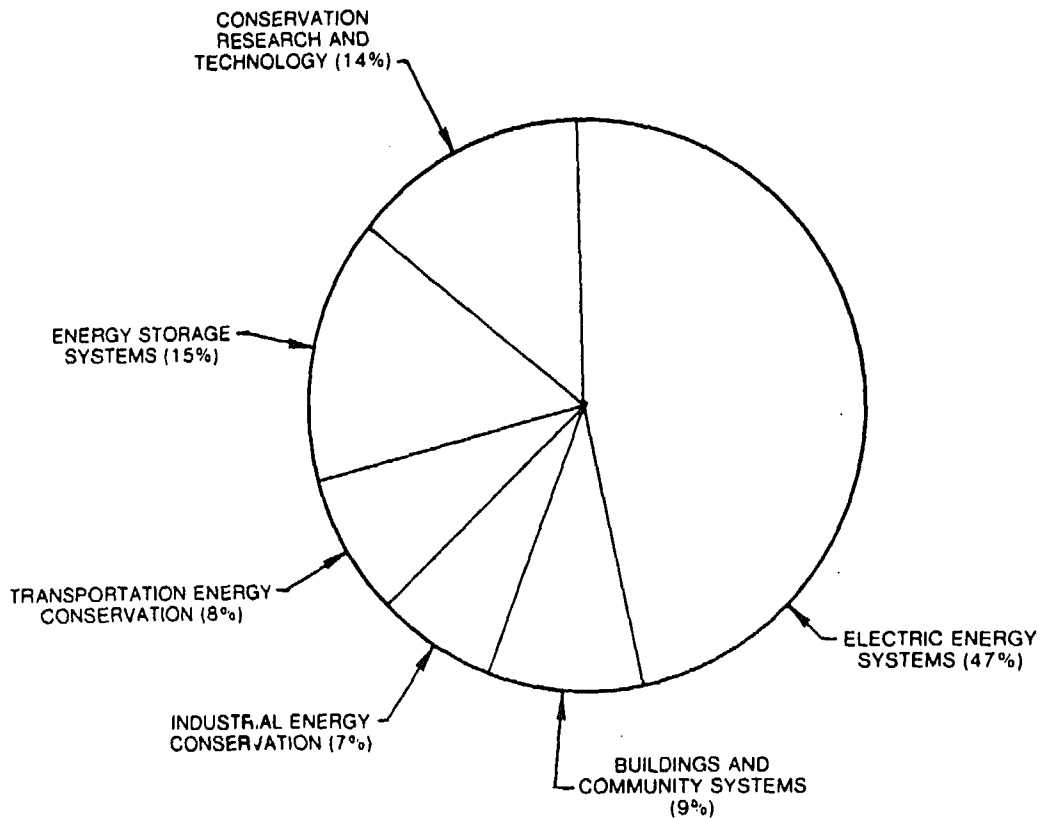


Figure 1. Distribution of Environmental Control Technology Funding in the Office of the Assistant Administrator for Conservation

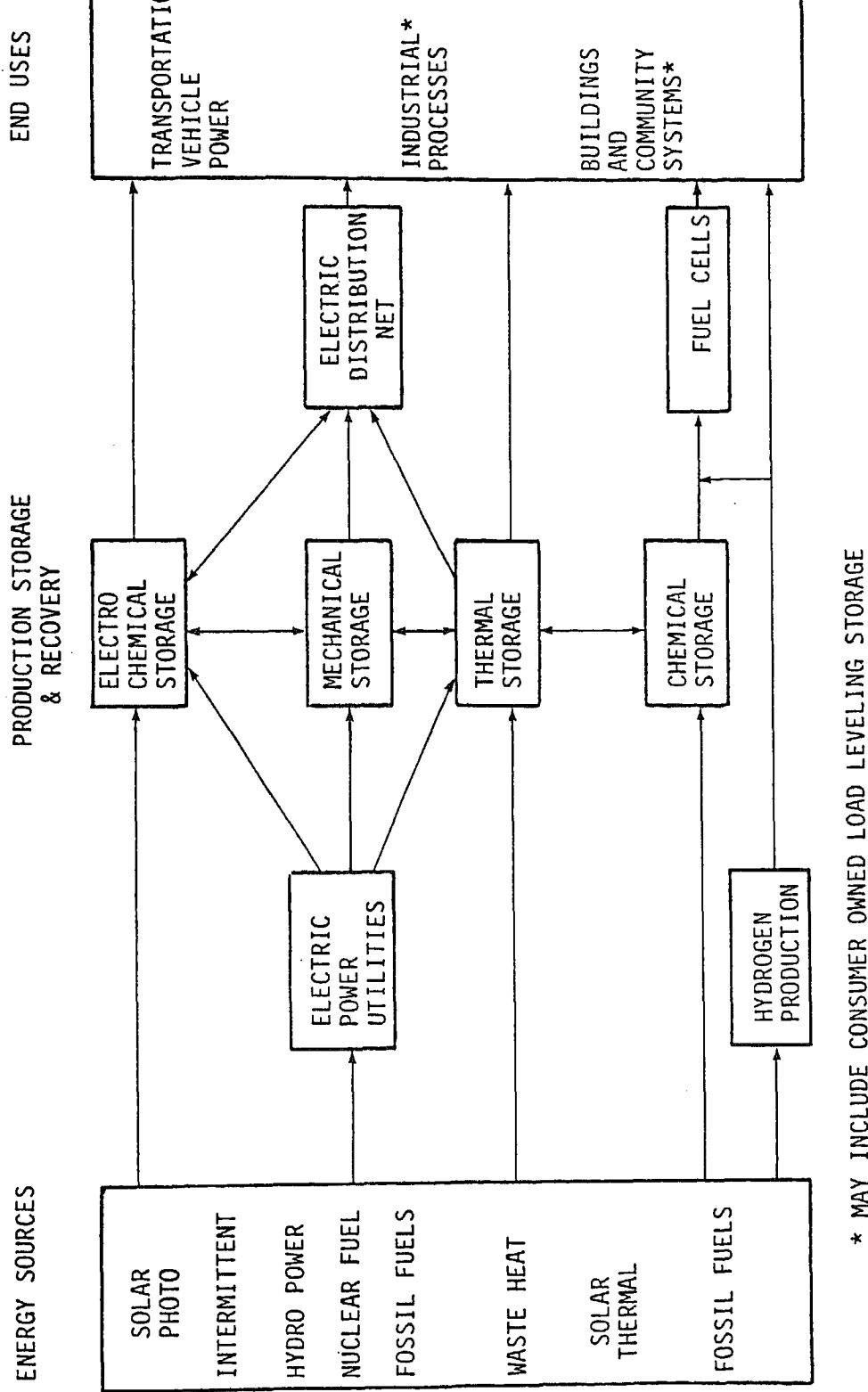


Figure 2. Flow Diagram of Energy Sources, Energy Storage Systems, and End Uses

* MAY INCLUDE CONSUMER OWNED LOAD LEVELING STORAGE

investment decision-making is the availability of accurate and complete information. Wally Schirra, U.S. Astronaut of Apollo 7, has stated (2),

"Extraordinary achievement begins with information. Make that information easily and instantly accessible and you set your energies free to explore the upper limits of the possible..."

Given finite budget resources, STOR's expanding role in promoting research on vital energy storage systems requires that careful attention be paid not only to the process operation but also to the environmental implications of the construction and operation of each research, demonstration, and commercialized system.

The Technical and Economic Analysis (TEA) Subprogram of STOR provides the Division with analytical and information management methodologies for use in supporting its program objectives. To this end TEA's technology assessment and R&D program evaluation activities have resulted in the development of recommended criteria for making R&D funding decisions, recommended schedules for the development of specific energy storage technologies, and the prioritization of energy storage options for transportation. These activities will continue during FY 1978 with further development of:

- R&D evaluation methodologies
- Assessment of environmental implications
- An integrated technical/management information system
- Assessments of specific end-use applications for energy storage technologies.

To integrate environmental considerations into the Energy Storage R&D Program Planning, the Technical and Economic Analysis Subprogram develops methodologies to:

- Incorporate environmental considerations into the planning process at the appropriate stage
- Resolve environmental issues concurrently with technology development

2. PLANNING AND EVALUATION

The Federal role in developing energy storage technologies calls for support of R&D in areas where private firms are unwilling or unable to invest, but in which significant national benefit is anticipated. The first step is to identify options with the greatest potential market impact, and to conduct theoretical and experimental programs to select the best options for further development. Second, proof-of-concept tests are performed to validate laboratory test results.

An evaluation of the potential environmental effects of interacting technologies are determined to assist in decisions regarding their future applicability for commercialization.

To accomplish these goals, STOR has adopted the following strategy (2):

- Identify energy systems that could benefit from the use of energy storage technology
- Identify appropriate energy storage technologies for use in these systems
- Initiate theoretical and experimental programs to select the best technology options for further development
- Perform proof-of-concept tests to validate laboratory test results on a pilot plant scale
- Evaluate the environmental implications
- Encourage rapid implementation of storage technologies through cost sharing and other incentives to industry.

Four main subprograms have been established to implement this strategy in specific technology areas. They are:

- Battery and Electrochemical Systems
- Chemical and Thermal Energy Storage Systems

These subprograms and their relationships within the decision are shown in Figure 3 (3).

To provide adequate information support for the requisite technology assessments, TEA is developing a Technical/Management Information System (TMIS) that will integrate into one coherent system the information required to perform a wide range of analyses on STOR technology development activities. Figure 4 is a diagram of the interrelated activities. The TMIS is the focal point for TEA's information management activities. It will integrate the wealth of information and data generated by energy storage research/analysis activities and make it readily available to STOR managers. TMIS will also make it possible to incorporate into STOR program decision-making processes the outcome of cost/risk/benefit assessments conducted on energy storage technologies. Parallel and integral to the program development is the development of methodologies for solution of environmental concerns. This parallelism and integration is shown in Figure 5. Development of workable environmental standards can be achieved only by considering the environmental problems and solutions to these problem immediately after concept formulation. Solutions to environmental concerns must be started along with laboratory development of the system if control technology is to be developed by the time the system is ready for commercialization.

The various levels of sophistication of the data that will be integrated by the TMIS are illustrated in Figure 6. The data at each level will come from a variety of sources. Some of these will be data bases which are already in existence; other sources will be data bases that will be established specifically in support of STOR activities. At present, TEA is assisting the other STOR subprograms compile the following data bases for inclusion in TMIS:

- Technical project evaluations
- Energy storage costs
- Measurements of material properties
- Evaluated data of material properties
- Environmental, health and safety data
- Bibliographic information

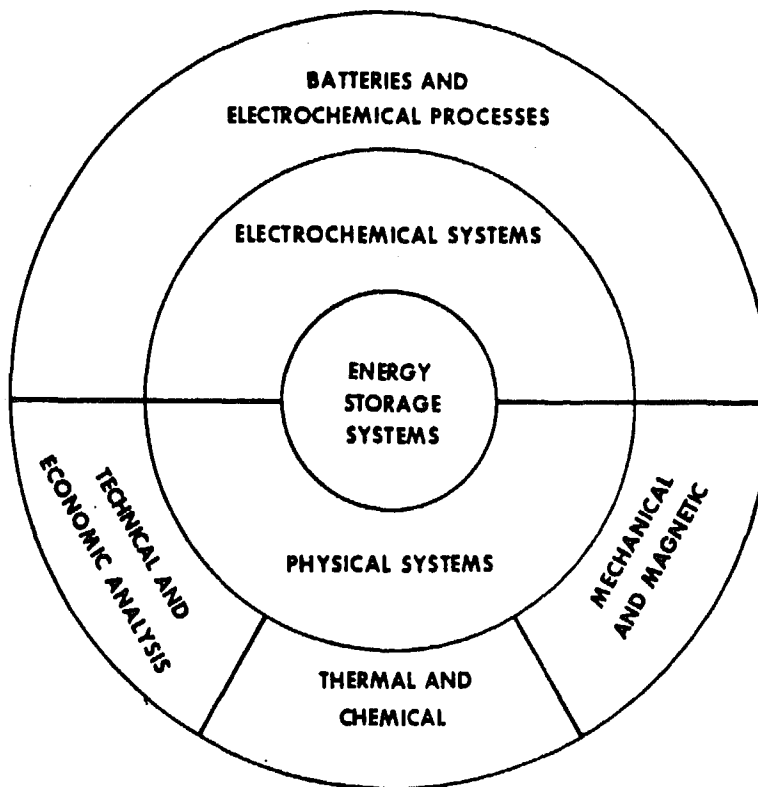


Figure 3. Subprogram Areas

TECHNICAL AND ECONOMIC
ANALYSIS SUBPROGRAM

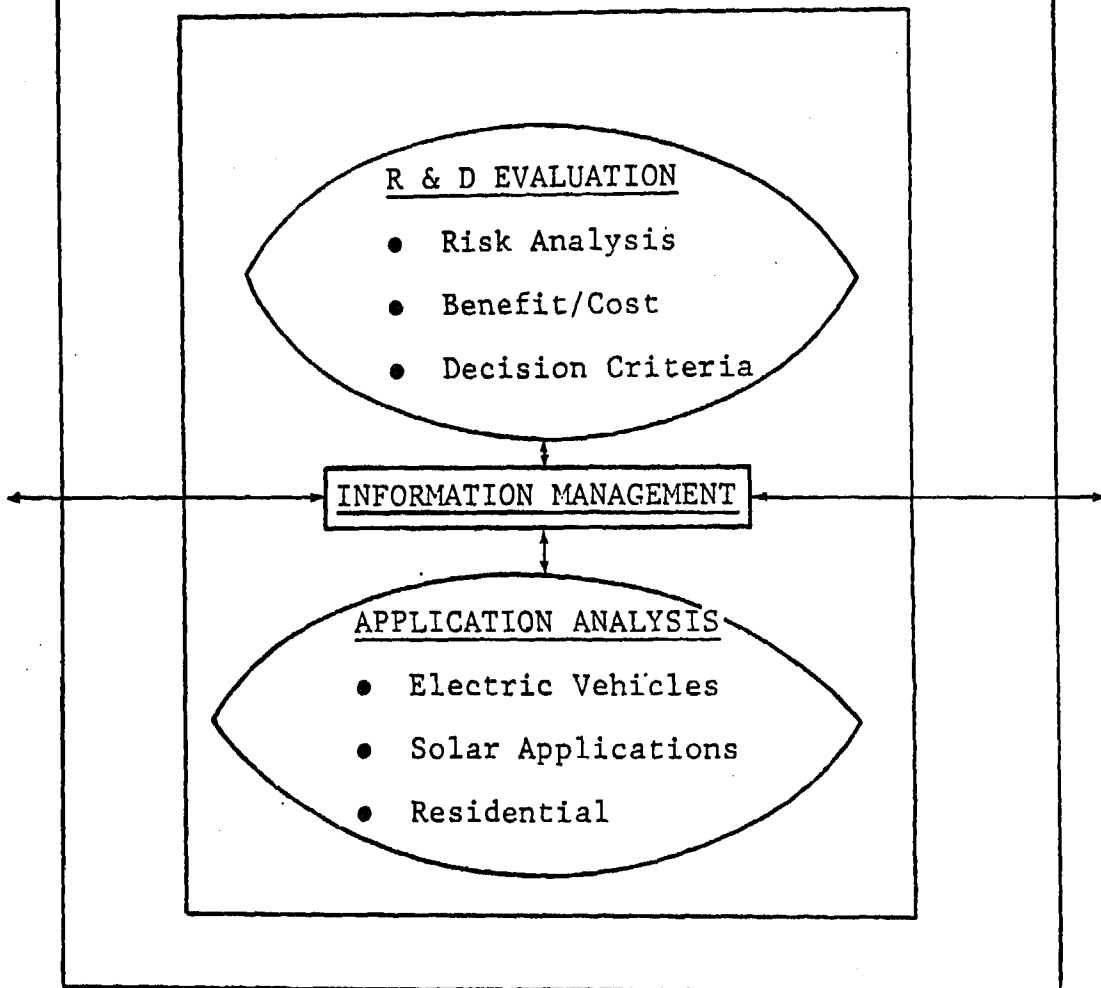


Figure 4. Technical and Economic
Analysis Subprogram

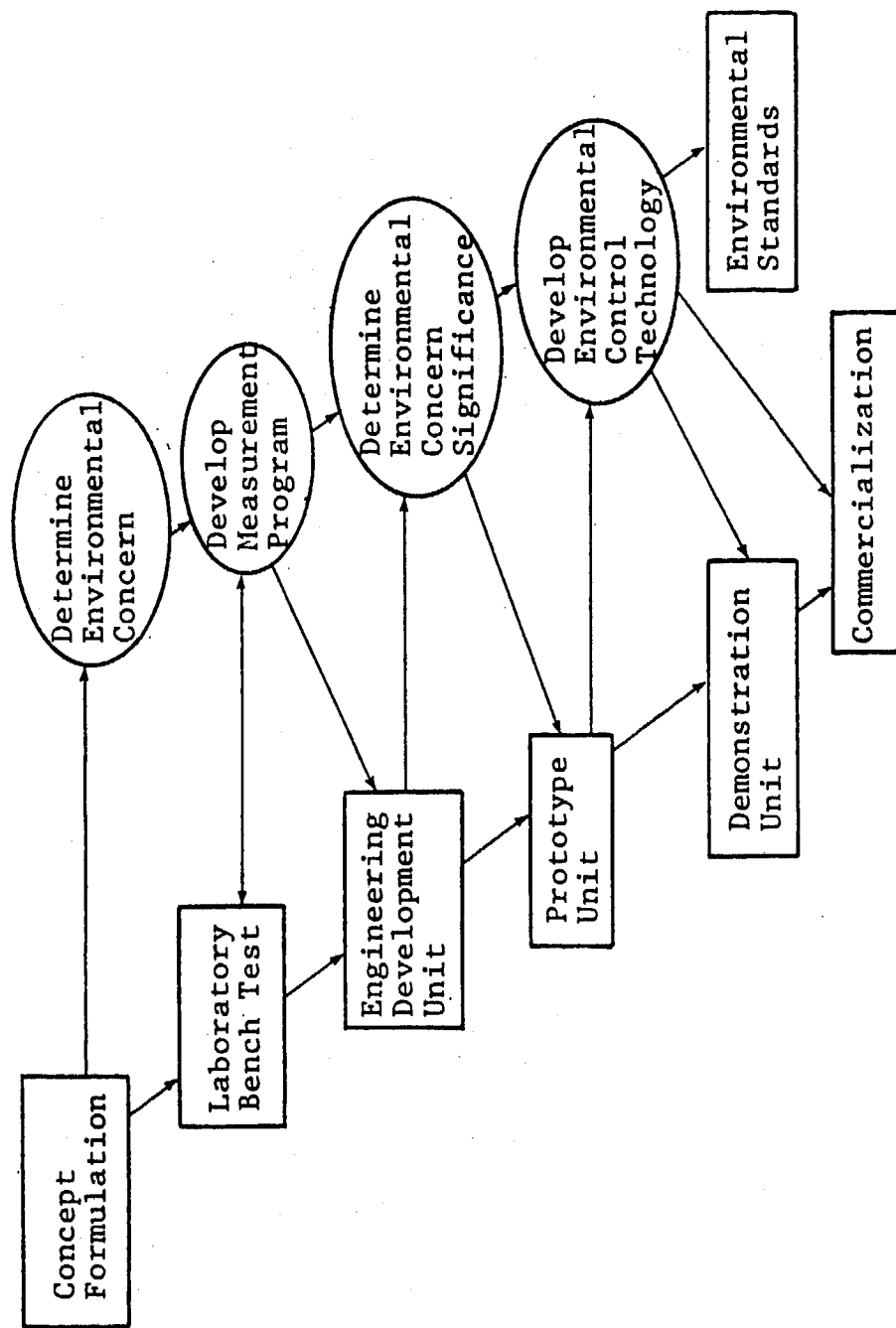


Figure 5. R&D Development and Environmental Development

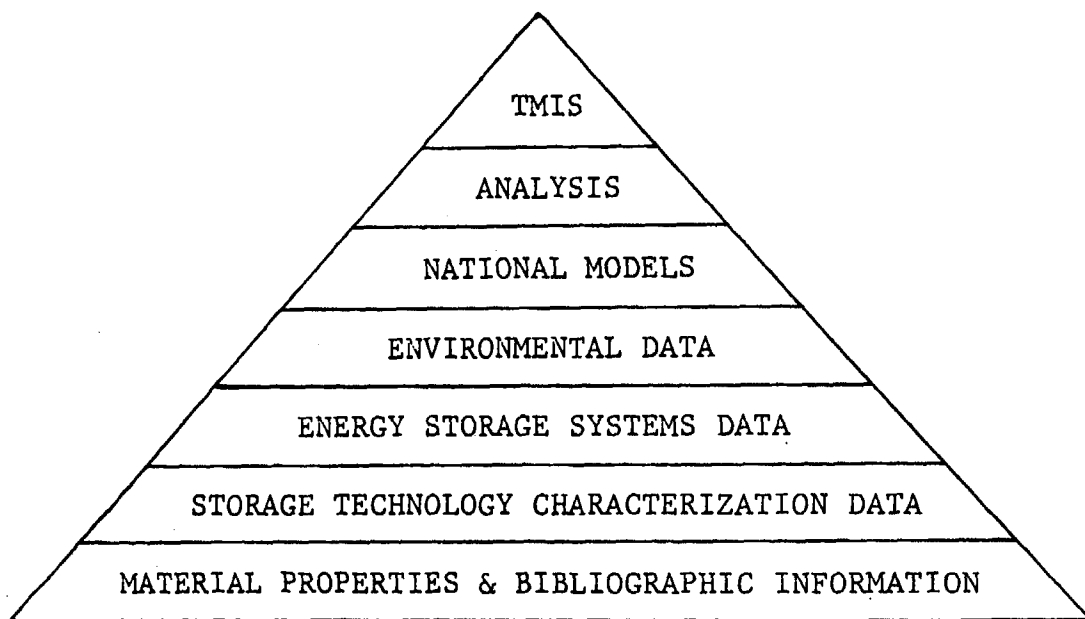


Figure 6. Technical/Management Information
System Levels of Data

- Project summary data.

Other data bases external to STOR but which have utility for STOR evaluation and review purposes are also being identified for integration into TMIS.

3. ENVIRONMENTAL CRITERIA

The requirement for considering environmental concerns in R&D planning stems basically from the National Environmental Policy Act (NEPA) of 1969 (PL 91-190), which became effective January 1, 1979 (4). This act proposes to insure that balanced decision making occurs in all development projects and that it includes technical, economic, environmental, social, and other factors. Complying with the requirements of NEPA involves the following series of activities designed to determine the interaction of any development project with the environment:

- The Environmental Inventory (EI) is a complete description of the environment as it exists in an area where a particular action is being considered.
- The Environmental Impact Assessment (EIA) is an evaluation of the consequences of a proposed action on each of the parameters as defined in the environmental inventory. The basic steps in the assessment process are:
 - (1) Prediction of the anticipated change in the environmental description
 - (2) Determination of the magnitude or scale of the particular change in the environment
 - (3) Application of an "importance factor" to the change.
- The Environmental Impact Statement (EIS) is a summary of the environmental inventory and the environmental assessment. This document is prepared either as a Negative Declaration (ND) if no environmental impacts are identified, or as a draft of the environmental impact statement (DEIS) from which the EIS develops (4).

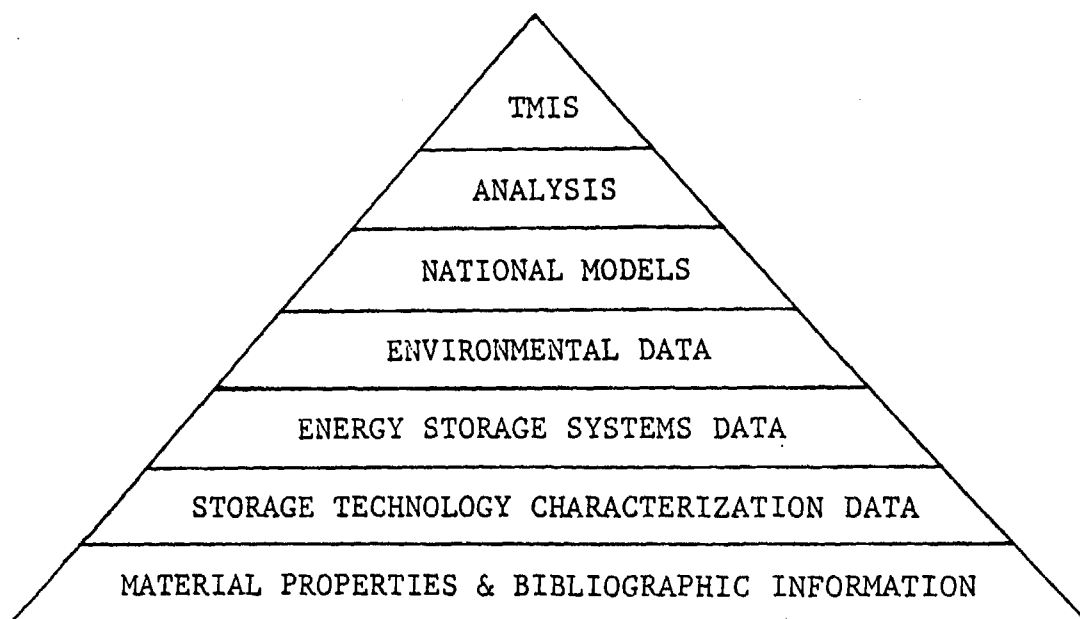


Figure 6. Technical/Management Information System Levels of Data

- Project summary data.

Other data bases external to STOR but which have utility for STOR evaluation and review purposes are also being identified for integration into TMIS.

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environmental effects, and the possibility of negative public reaction or social impact. Figure 7 shows a screening procedure decision tree for identifying where environmental actions are required during the current planning horizon. Projects are considered for inclusion in the EDP only if they have:

- Major decision points within the following 1.5 years that preclude further R&D options
- Full-scale commercial demonstration within three years
- Expected full-scale commercialization within five years (5).

A second screening occurs following a preliminary assessment of the possible adverse environmental effects of the technology. This assessment considers materials required for the technology, components operation, and by-products, as well as those materials consumed in the retirement and disposal of components or by-products. If a project has inherent adverse environmental effects, the magnitude of these effects is then considered. In assessing impact magnitude, consideration is given to the commercial potential, anticipated application, and siting characteristics associated with the technology. All projects where no environmental action is required are subjected to a fourth screening criterion -- negative public reaction. Projects with the potential for creating negative reaction from the public, industry, or government, are included in the EDP.

To provide adequate information support for technology assessments, the TEA has developed a TMIS to integrate the information required to perform a wide range of analyses on energy storage technology developments into one coherent system. A flow chart of the environmental input to TMIS is shown in Figure 8.

Environmental concerns must be ranked in order of importance so that those concerns that can produce the greatest environmental effects can be assessed relative to environmental benefits for appropriate inclusion in R&D program planning. Two generalized types of environmental concerns have been defined by the DOE:

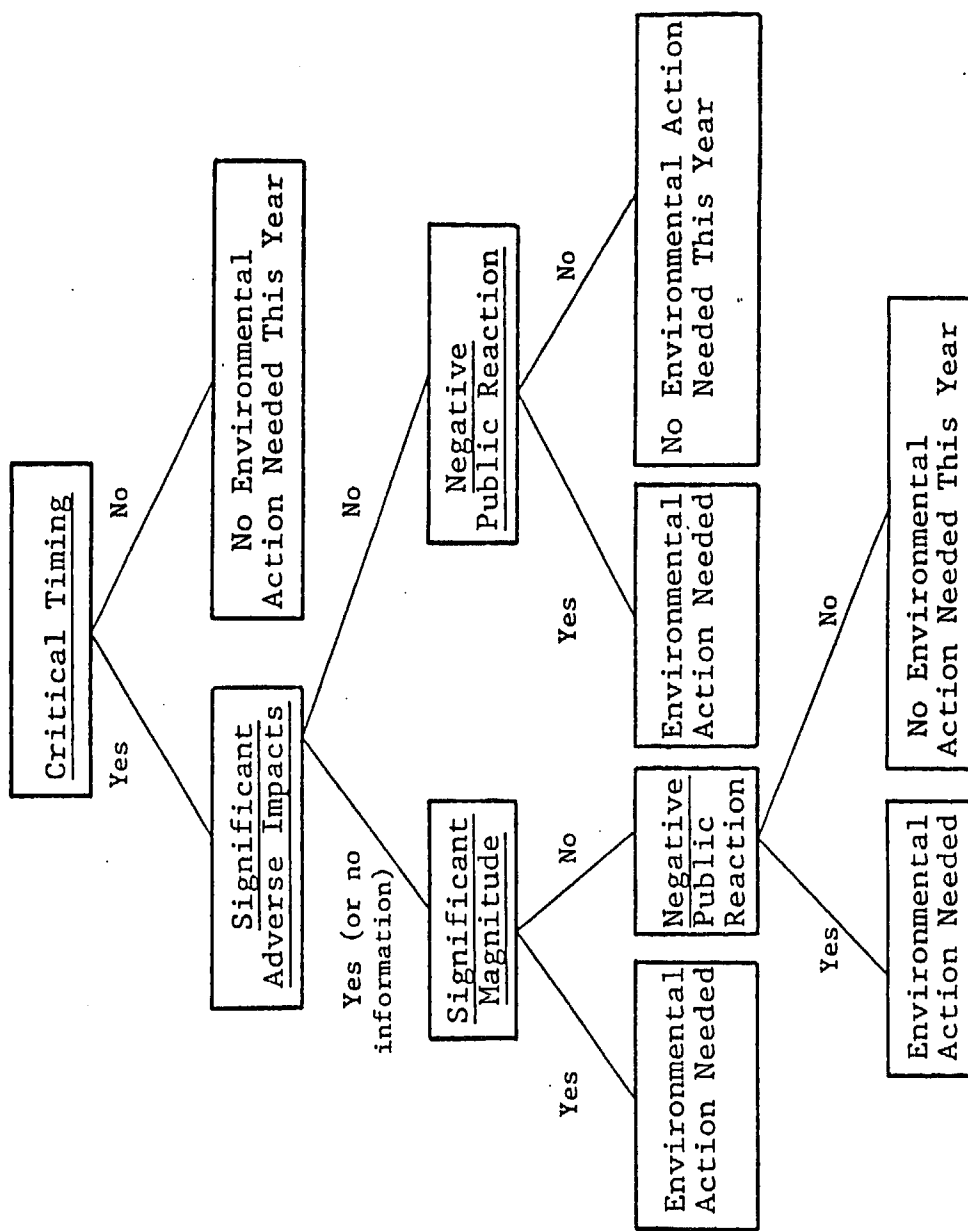


Figure 7. Screening Procedure Decision Tree

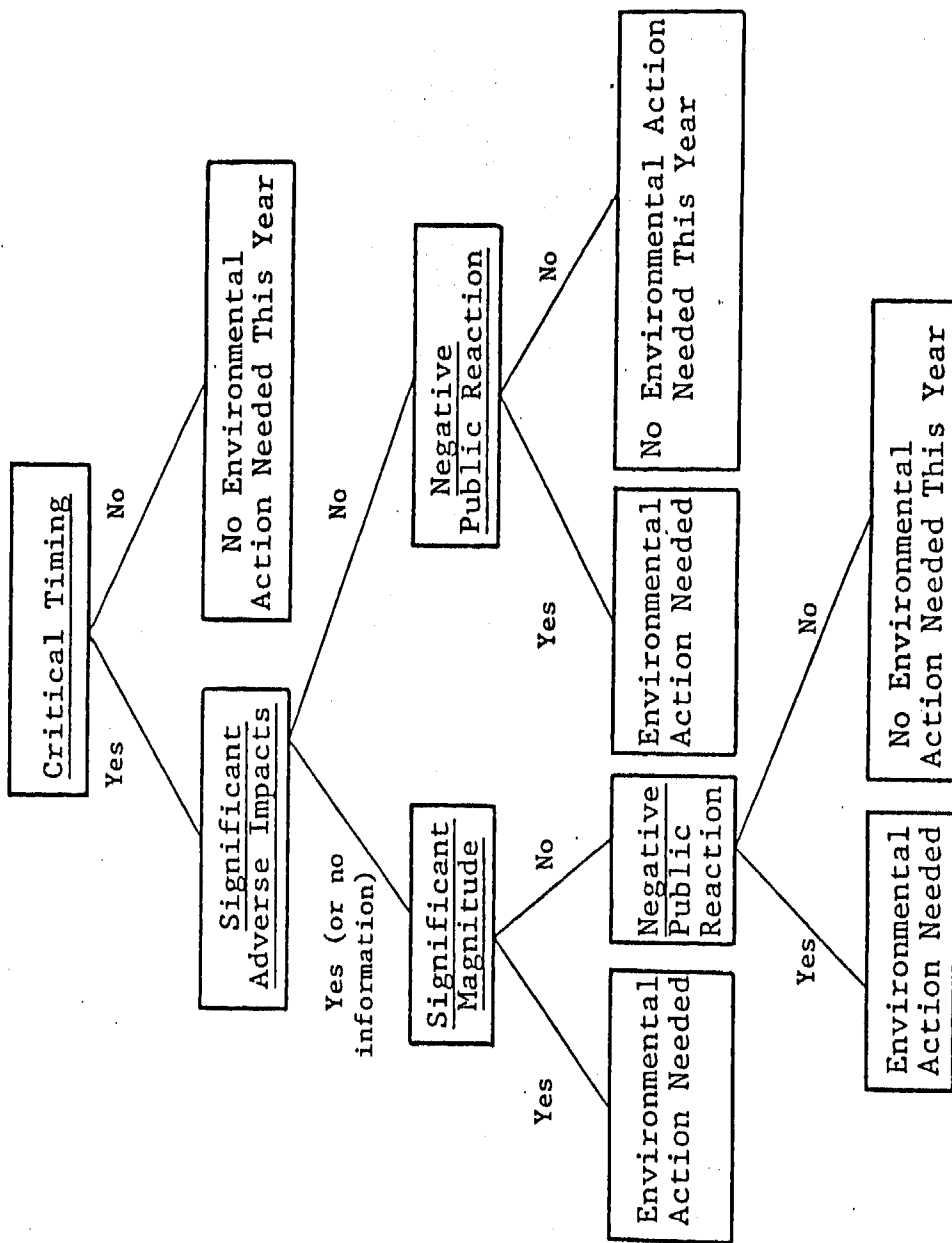


Figure 7. Screening Procedure Decision Tree

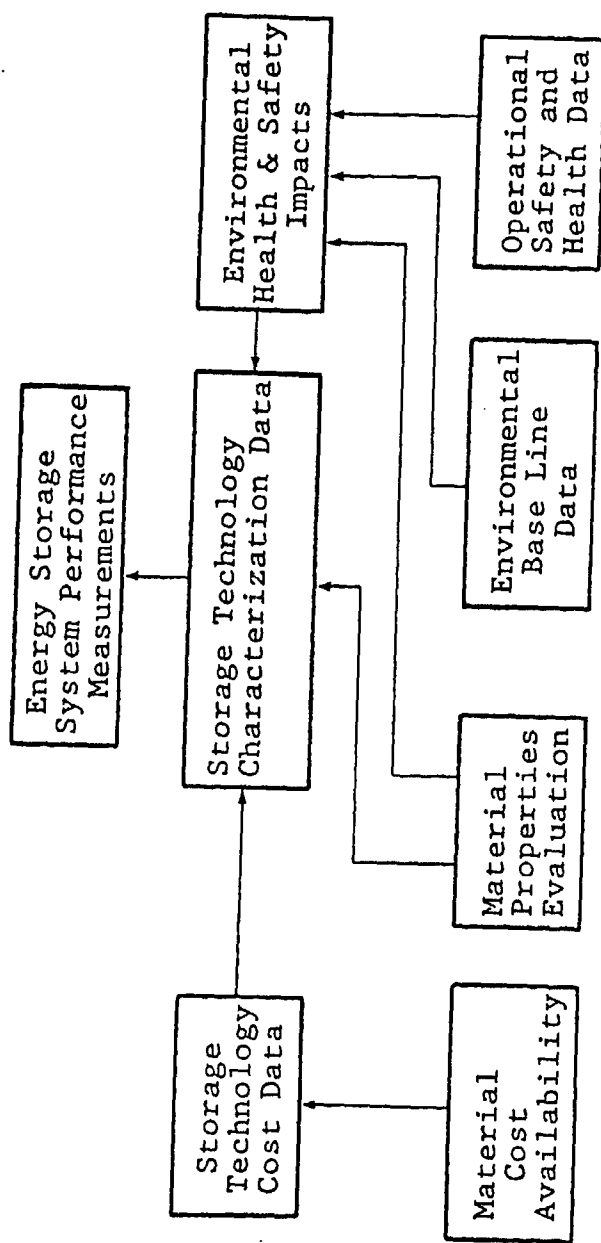


Figure 8. Environmental Input Into Technical/Management Information Systems Development

- Exploratory concerns, for which there exists inadequate knowledge to explain or estimate underlying cause/effect relationships or to quantify the potential environmental impact, whether negative or positive
- Problematic concerns, for which some understanding of the cause/effect relationship exists or the magnitude of potential negative environmental impacts can be estimated (5).

Concerns of the first category require research, since sufficient knowledge is not available to determine the impact of the technology. Concerns in the problematic area are evaluated or ranked accordingly (6):

- Are the conditions that produce the environmental concern expected to emerge before 1982?
- Does the environmental R&D time necessary to resolve the concern approximate or exceed the impact emergence time?
- Are the conditions that are producing the concern expected to have a severe impact on human or other elements of the environment?
- Will a large segment of the population be affected even if the severity of the potential impact is marginal?

Results of this ranking process provide the DOE with an identification of the primary concerns associated with the energy storage technologies. Environmental research and development activities include:

- Identification of concern
- Problem characterization and measurement
- Transport and fate of pollutant
- Evaluation of effects
- Problem resolution.

Table 1 shows the coding established to denote the sequencing of required activities for any particular environmental concern. If applied to batteries, for instance, concerns for air and water quality would be rated at Level 0 for R&D status, since the effluent streams from battery manufacture

Environmental Concern	Level of Research (R&D Status)*
<p><u>Physical Environment</u></p> <p>Air and Water Quality</p> <ul style="list-style-type: none"> The manufacture of battery components will generate solid and liquid wastes as well as atmospheric emissions. These effluent streams have not been fully characterized. <p><u>Available Resources</u></p> <p>Material</p> <ul style="list-style-type: none"> The use of lead in lead-acid batteries may constitute a significant part of the total national consumption of this metal. Current industrial practices for recovery and recycling of lead from batteries have not been examined in depth in terms of efficiency, cost, and environmental impact. Battery design to minimize material use and to maximize recyclability has to be identified. <p><u>Health</u></p> <p>Occupational and Public</p> <ul style="list-style-type: none"> The threshold limit values for lithium metal and compounds, primarily those compounds associated with the manufacture of lithium/metal sulfide batteries, have not been established. The extent to which nickel carbonyl (a known carcinogen) will be produced as a byproduct of Ni/Fe and Ni/Zn battery production is unknown. Human health effects due to chronic and low-level exposure to stibine and arsine generated during lead-acid battery overcharging is unknown. 	<p>0</p> <p>0</p> <p>I</p> <p>I</p> <p>I</p>

- * 0 - Identification of concern
I - Problem characterization and measurement
II - Transport and fate of pollutant
III - Evaluation of effects
IV - Problem resolution

surement are lacking.

4. ENVIRONMENTAL CONCERNS

Utilization of the potential environmental concerns in program planning requires the evaluation of each program relative to concerns in the areas of:

- Physical environment
- Ecosystem
- Human environment
- Available resources
- Health
- Safety.

This evaluation results in a Primary Environmental Issues Map, shown in Figure 9. Each of these concerns, along with its magnitude, human effects, and potential mitigation is considered in planning for commercialization of the various energy storage programs.

5. CONCLUSION

A brief description of the method by which environmental concerns are integrated into the STOR's planning efforts has been presented. An overview of these environmental concerns shows the wide range of factors that must be considered in the planning process. It is, however, necessary to consider both the environmental concerns and environmental benefits at each major decision point of the energy storage technology development.

NEPA requires that an environmental impact assessment be performed to describe the environmental consequences of "any planned actions" (4). A detailed evaluation is necessary to determine if any environmental consequences could result from the planned program. If any environmental

Classification of Environmental Concerns	Subprogram	Chemical/Thermal		Mechanical/Magnetic				Batteries/Electrochemical					
	Technology or Project	Thermal	Thermo- Chemical	FESS ¹	CAES ²	UHPS ³	SMES ⁴	Hydrogen	Pb-Acid Battery	Zn-Cl Battery	Na-S Ceramic and Glass Batteries	Li-S Battery	Ni-Pe and Ni-Zn
<u>Physical Environment</u>													
Air Quality					•			•	•	•	•	•	•
Meteorology													
Water Quality		•	•		•	•		•	•	•	•	•	•
Waste Disposal			•		•	•			•	•	•	•	•
Geology and Topology		•			•	•	•						
<u>Ecosystem</u>													
Terrestrial		•					•		•	•	•	•	•
Aquatic		•	•			•			•	•	•	•	•
<u>Human Environment</u>													
Land Use		•				•	•						
Water Use		•				•							
Aesthetics and Human Interest													
Socioeconomic		•											
<u>Available Resources</u>													
Material							•		•	•	•	•	•
Energy													
Water													
Land													
Societal							•						
<u>Health</u>													
Occupational			•				•		•	•	•	•	•
Public		•			•	•	•		•	•	•	•	•
<u>Safety</u>													
Occupational		•	•	•	•		•	•	•	•	•	•	•
Public				•	•	•	•	•	•	•	•	•	•

¹ Flywheel Energy Storage System.

² Compressed Air Energy Storage.

³ Underground Hydroelectric Pumped Storage.

⁴ Superconducting Magnet Systems.

Figure 9. Energy Storage Systems
Primary Environmental Issues Map

main assessments are (4):

- Description of the environmental impact of the proposed action
- Identification of any adverse environmental effects which cannot be avoided should the proposal be implemented
- Discussion of alternatives to the proposed action
- Description of the relationship between local short-term uses of man's environment and the maintenance and enhancement of long-term productivity
- Discussion of any irreversible and irretrievable commitments of resources that would be involved in the proposed action should it be implemented.

In this manner the environmental concerns are identified and considered in all R&D planning and evaluation of energy storage systems.

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1.0 INTRODUCTION

Compressed air energy storage (CAES) is considered a viable technology for storing excess off-peak electrical energy from a grid in thermal-mechanical form, and recovering it later for peak-time generation of electricity. As such, its major benefit would be the substantial savings in the consumption of premium fuels normally required for peak power generation. There is considerable economic and strategic benefit in such a savings, through decreased imports of petroleum. In order to promote the early commercialization of CAES technology, it is important that significant environmental concerns be identified and adequately characterized, so that environmental control planning can be an integral part of technology development.

The purpose of this paper will be to describe the on-going efforts of the CAES Environmental Control Concerns Program at the Pacific Northwest Laboratory (PNL). PNL, operated for the Department of Energy by the Battelle Memorial Institute, is the Lead Laboratory for DOE-sponsored research in compressed air energy storage. The Environmental Control Concerns (ECC) Program was established with the following objectives:

- identify the environmental factors associated with the use of CAES;
- quantify the environmental impacts of these factors, and establish a data resource useful for planning and siting CAES facilities; and
- identify environmental control practices or areas of research leading to improved control practices.

In this paper, the technologies of CAES will first be described briefly. The major environmental concerns will then be discussed, with known control practices.

2.0 CAES TECHNOLOGY

The demand for electricity is highly variable. As shown in Figure 1, a utility's demand load varies in a daily cycle, with the highest electricity requirements during daylight hours and the lowest at night. While the utility must have the capacity to supply the peak demand, it is clear that much of this capacity is idle part of the time. This demand picture is often handled by using:

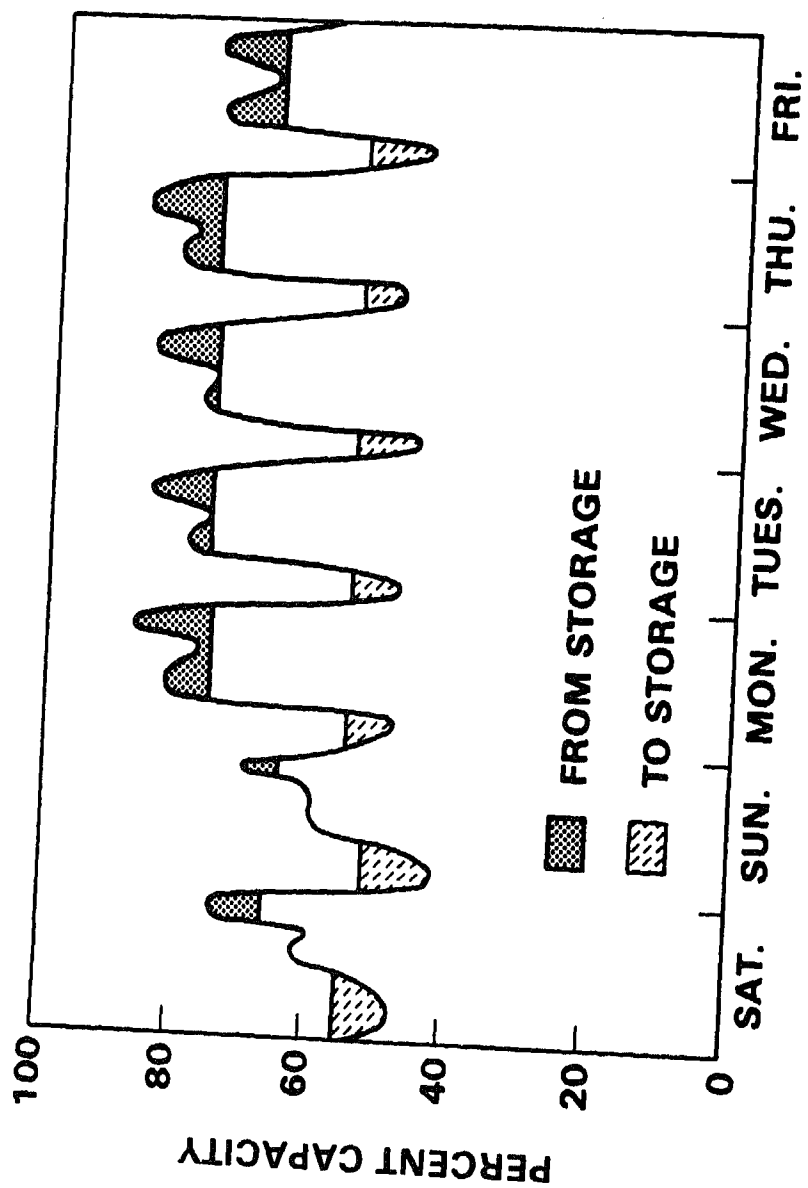


FIGURE 1. Weekly Electric Utility Load Curve

- peaking plants to provide for the very top of the daily and weekly cycles.

The peaking plants are often powered by gas- or oil-fired turbines although in some smaller utilities, diesel engines are used. Turbines are popular because they can be started quickly for relatively brief periods of operation.

Due to economies of scale, baseload power plants supply electricity at a lower cost than peaking plants. Utilities could lower generation costs and use less oil and gas if they could increase the utilization of baseload capacity. This could be done by operating the baseload plant at a higher level and storing the excess of supply over demand in another energy form, such as mechanical energy. The stored energy could then be converted back to electricity as needed to supply peak demand. Compressed air energy storage is one such mechanical storage scheme.

The major components of a compressed air energy storage system are: 1) the underground air storage chambers; and 2) gas turbine compressor/generator systems located above-ground. The basic concepts of operation are as follows (see Figure 2):

During periods of low electricity demand, the excess capacity of a remote baseload generating plant would be used to power an air compressor train at the CAES facility. The compressed air would then be stored underground. During daily peakload periods, when electricity demands exceed the capacity of baseload plants, the turbine generator would be fired up to supply additional electricity to the grid. The compressed air extracted from the underground storage region would be mixed with fuel, the mixture would be ignited in a combustion chamber, and the hot combustion products would be expanded through the turbine for power.

The key difference between the CAES turbine and a simple cycle turbine is that the compression and expansion portions of the cycle are performed at different times. By storing energy from baseload plants, an electric utility company would achieve a more effective utilization of its low-incremental-cost generating capacity. Since the peaking turbine would not have to power its own compressor, it can be sized smaller, and it would consume up to two-thirds less high-cost premium fuels (oil or natural gas) than the simple cycle turbine. Thus, the utility's overall requirement for additional high-cost peaking capacity would be reduced. There would be some loss of energy in storage because the air must be cooled following compression and reheated prior to injection into the combustion chamber. However, this is outweighed by the savings in cost of premium fuels.

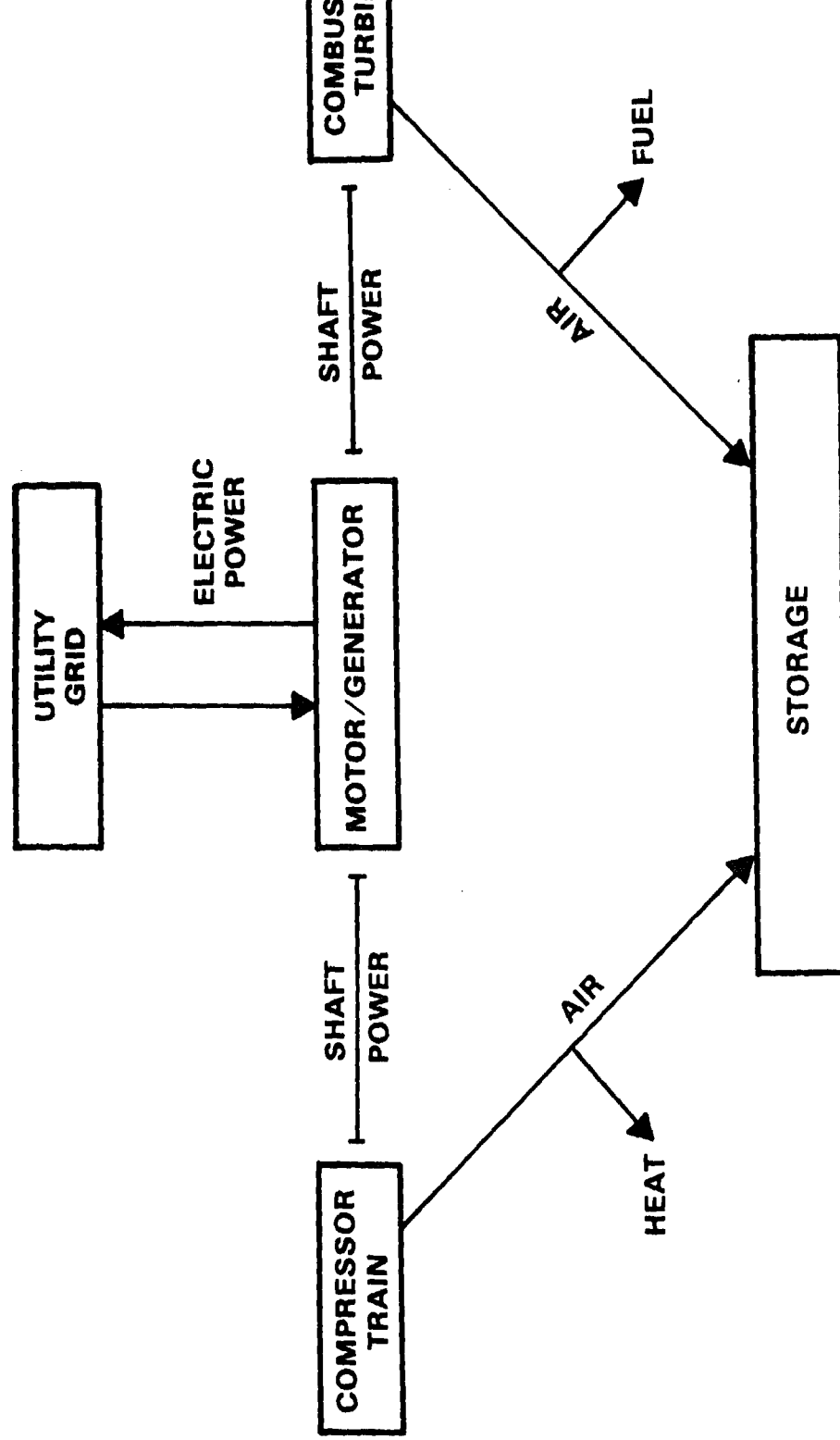


FIGURE 2. Schematic of Basic Compressed Air Energy Storage Cycle (Reference 1)

The first CAES facility to be constructed by a utility; Nordwestdeutsche Kraftwerke (NWK) of West Germany, is near operational status. The 290 MW plant, near Huntorf, will pump air into a solution-mined salt cavern for 8 hours each day, using 58 MW of excess system capacity. During peak daytime demand, it will generate electricity at 290 MW for 2 hours.

The basic types of underground reservoirs for the storage of air in a CAES facility include:

- 1) porous media, such as aquifers (see Figure 3);
- 2) mined hard rock caverns; and
- 3) solution mined caverns in salt formations.

The last two types may be in "compensated" or "uncompensated" configurations. Compensated reservoirs are operated at constant pressure by having a water-filled leg leading up to a surface lake (Figure 4). In this configuration, the cavern walls are exposed to much smaller daily air pressure variations than in uncompensated systems. Thus, the risk of adverse environmental impacts resulting from degradation of the cavern walls is also less. On the other hand, the compensating water leg represents a potential pathway for contamination of the surface reservoir. This necessitates sealing the bottom of the reservoir to prevent seepage downward to the water table, and an eventual problem of cleaning or disposing of the reservoir waters.

3.0 RESERVOIR STABILITY AND ENVIRONMENTAL CONCERNS

A significant potential problem in CAES implementation is the stability of the underground reservoir. A great deal of knowledge concerning the utilization of such reservoirs is available from decades of experience in the subsurface storage of natural gas, helium, and liquid fuels. However, the operation of a CAES reservoir is different in that the subsurface medium would be subjected to relatively rapid temperature, pressure, and humidity fluctuations as the air is injected or withdrawn in daily and weekly cycles. This compares with the seasonal cycles of natural gas storage. The thermo-mechanical stresses to which the confining rock would be subjected during compressed air storage cycles are not satisfactorily understood and are being investigated. Cyclic stresses and geochemical reactions might lead to degradation of the rock, and cavern failure. This is of environmental as well as technical concern, because a cavern collapse could have surface manifestations, such as subsidence, or the sudden release of contaminants to the air or groundwater.

The establishment of design criteria to ensure the successful operation and long-term stability of CAES caverns is the goal of the Reservoir Stability and Design Criteria Program at PNL. This program

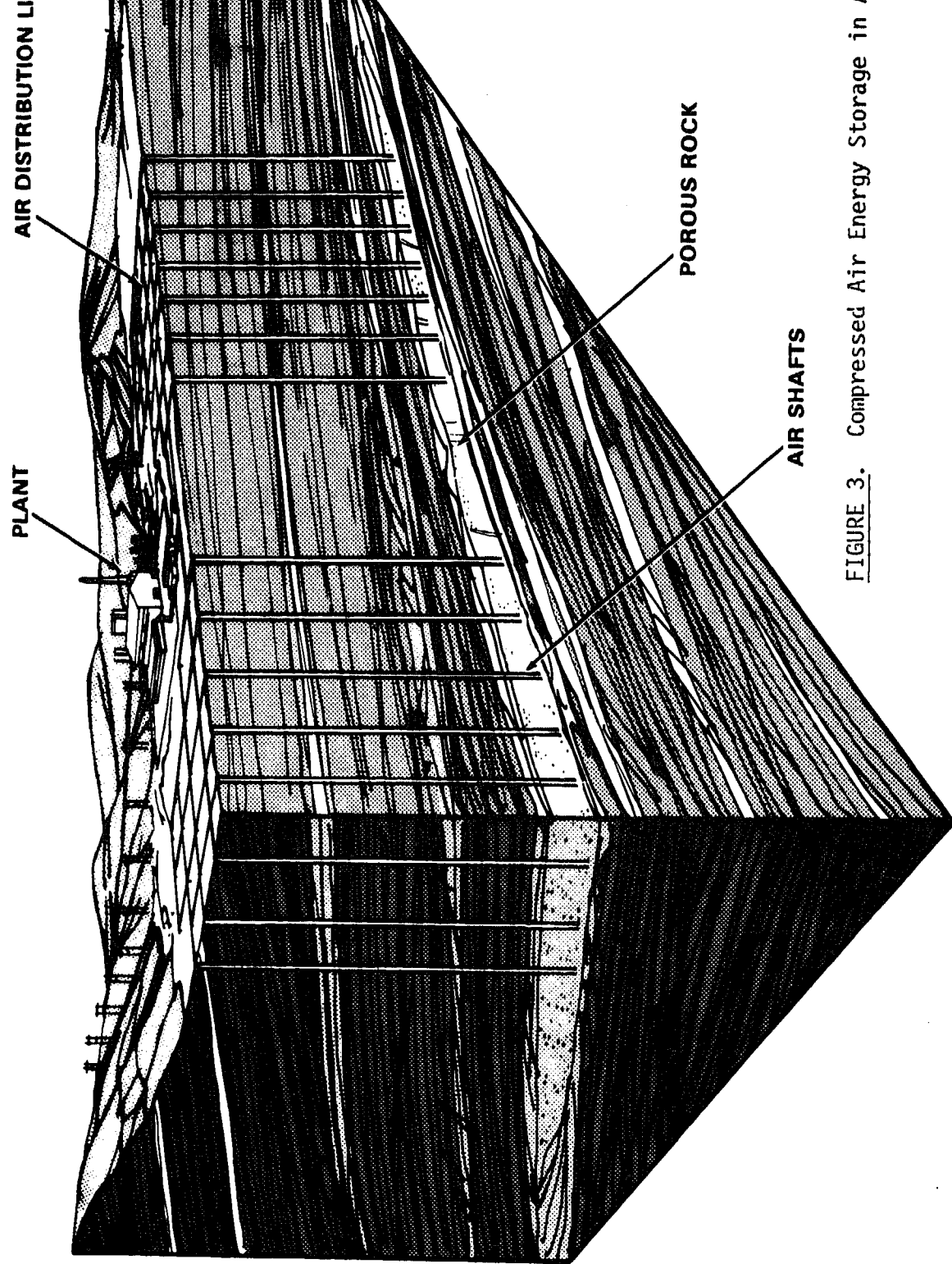


FIGURE 3. Compressed Air Energy Storage in a

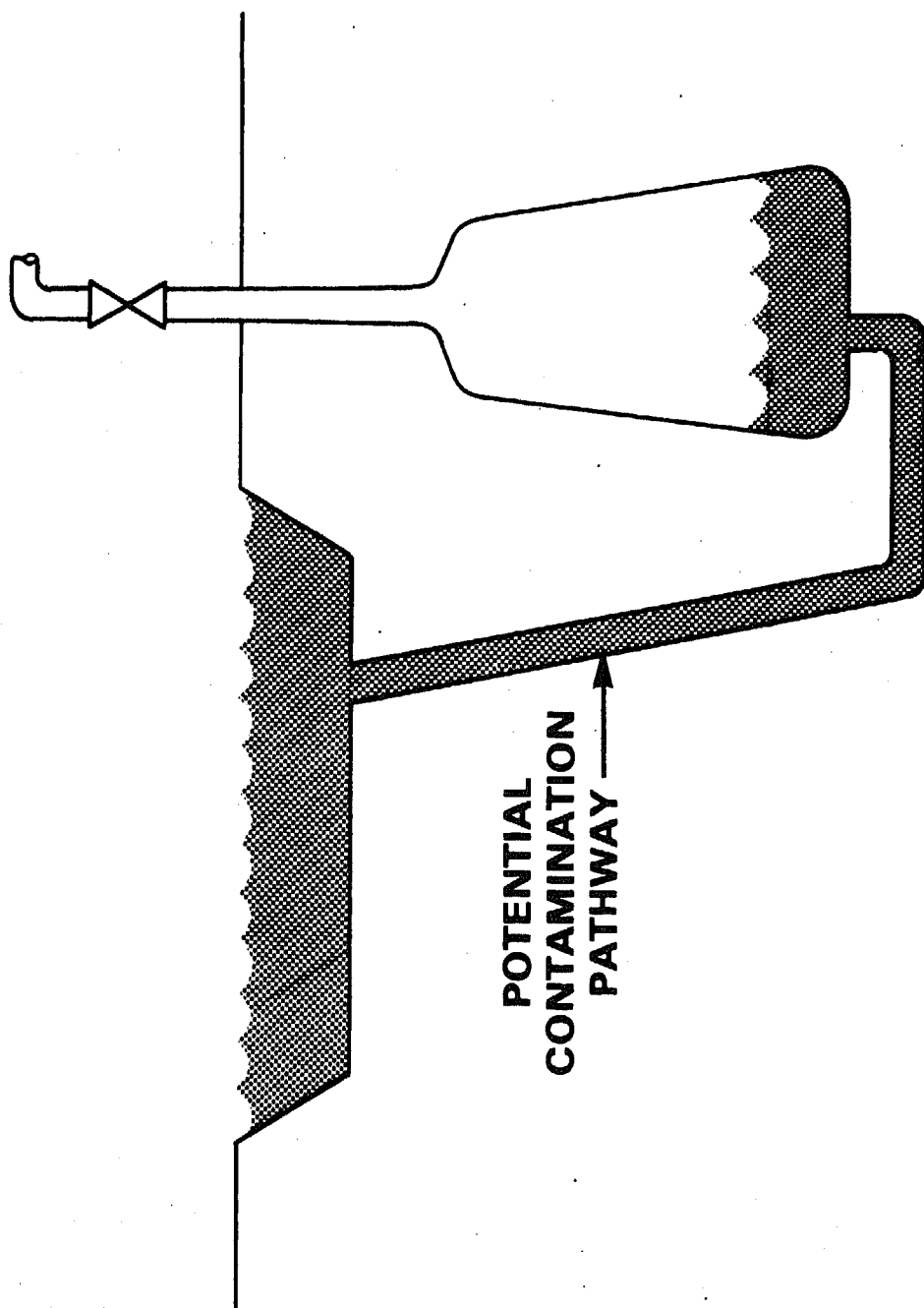


FIGURE 4. Compensated Storage

4.0 ENVIRONMENTAL IMPACT AND CONTROL

The CAES-ECC Program is concerned mainly with comparing the potential environmental impacts of a conventional peaking turbine facility and those of a facility which incorporates compressed air energy storage. That is, the baseline for comparison is the simple cycle turbine and we are interested in those differential impacts due to the addition of CAES components. Differential concerns may involve either the above-ground components of CAES or those below ground.

In this section, the major potential impacts that have been identified will be presented. Many of these are common to other technologies and environmental control practices are already available. Areas of research planned at PNL to address environmentally related issues, leading to development of control strategies, will be pointed out.

A major element of environmental control for CAES is proper site selection. Particularly, the site-specific geology determines the likelihood and nature of adverse impacts. The siting of caverns in a porous medium, salt dome, or in hard rock each has its own particular set of environmental concerns.

The environmental concerns can be classified as follows:

- air quality impacts;
- water quality impacts;
- impacts on geologic structures; and
- aesthetics and land use considerations

These will now be discussed separately.

Air quality impacts

Potential impacts result from construction activities, heat rejection, cavern carryover, leaks, and turbine exhaust products. Construction activities result mainly in fugitive dust emissions from disturbed land and combustion emissions from machinery. For CAES utilizing conventionally mined caverns, additional fugitive dust emissions may result from the ventilation of underground cavities during mining operations and the piling of tailings on the surface. However, control practices currently exist and no R&D is required.

Heat rejection results from the need to lower the temperature of the compressed air before injecting it below ground. Standard cooling towers may be employed to dissipate heat to the atmosphere. Or, an advanced CAES system could involve storing the heat underground in a

densible gases entrained in the extraction air stream. Water vapor condensation in the atmosphere could result in local fog or mist problems. Designing for tolerable ranges of temperature and humidity of the reservoir air in the vicinity of the wellbore are major factors in controlling the condensation problem. Studies are underway at PNL to determine air temperature and humidity distributions in a porous medium reservoir. Particulates can result from microfracturing or spalling of reservoir rock material. Possible erosion of the turbine blades due to particulates as well as air quality standards may limit the allowable particulate content. Filtering of the air stream may be practical, but research aimed at slowing degradation of the rock is required. Combustible gases mixed with the extraction air may cause explosions in surface facilities. Sulfur gases from the reservoir would aggravate air pollution due to fuels combustion. However, these problems might be eliminated with careful site selection.

Air leaking from the reservoir might also carry pollutants up to the surface.

Air pollution emissions due to fuels combustion should be less at CAES peaking plant sites than at conventional turbine plant sites. As mentioned previously, a CAES turbine consumes only about one-third as much oil or gas than a simple cycle turbine. The remaining fuel load, to provide the compression energy, is transferred to a baseload plant. If this is a nuclear plant, there are no additional combustion emissions. A coal plant, however, will have additional emissions which at least partly offset the reduction at the CAES site. The net air quality impact may be positive, since economies of scale may be at work in controlling emissions at the baseload plant.

Water quality impacts

These can be divided into surface water impacts and subsurface water impacts.

Surface water impacts result during the construction phase due to runoff into nearby streams or lakes. Spills of drilling wastes (muds) are possible, as well as fuel spills from storage tanks. Existing control practices are applicable.

For CAES in hard rock caverns, leaching of toxic substances from mine tailings piles is a major potential concern. This problem will be a focus of CAES-ECC investigations in FY-1979. As much as one million cubic meters of mine tailings may be produced in the excavation of the largest CAES caverns. Site selection may be a major factor in pollution control, by careful selection of stable, innocuous mineral types. Experience from strip mining operations will be useful in formulating strategies to control runoff from tailings piles. Another possibility is to sell the tailings for productive use. This approach would have the advantage of offsetting part or all of the costs of excavation.

Subsurface water impacts involve the potential contamination of underground drinking water supplies. Although CAES reservoirs ideally are isolated from potable water aquifers (by being sited below potable water, in saline aquifers, or within salt domes), potential contamination pathways may develop during operation. The injection well itself is a potential concern. It is likely that CAES wells will be subject to currently proposed EPA regulations (40 CFR Part 146) on subsurface injection wells. The nature of the CAES operating cycle, however, raises some concern about the long-term integrity of the well casing and completion cement, especially in the vicinity of the storage zone. The thermomechanical stresses due to relatively rapid pressure and temperature changes might result in casing or cement failure. This could open a pathway along the casing for vertical migration of water. The Reservoir Stability and Design Criteria Program is addressing this problem. Cross-aquifer communication would be aggravated by the possibility of biological contamination introduced with the injected air or chemical contamination as the result of geochemical reactions of the air with the rock.

Air leaking from the reservoir and percolating upward may collect in potable aquifers. This could impact the flow rates of wells in the area. Also, if the air contains contaminants, these could effect water quality. Techniques to control air leaks from caverns by the use of vent wells and water curtains are known from natural gas storage experience. In the water curtain concept, water is injected to pressurize rock formations overlying the reservoir and caprock. The pressurized formations act as effective barriers to air migrations. Vent wells recover any air which does leak out.

Compressed air storage in an aquifer could potentially alter the aquifer flow pattern, but this is a concern which could be eliminated during site selection.

In salt cavern storage, disposal of brine from the solution mining process (Figure 5) is a concern. Subsurface injection of brine into deep saline aquifers is a common practice in the petroleum industry. Whether or not contamination of potable waters by injected brine represents a significant risk has not been conclusively determined. However, because water migration in aquifers is so slow, contamination may not be detected for decades, hence subsurface injection should be considered with caution. This problem has been addressed in a number of related programs, including the Geothermal Liquid Waste Disposal Program at PNL, the National Waste Terminal Storage Program, and the Strategic Petroleum Reserve Program. It appears that proper well design (Figure 6), which adheres to the proposed EPA regulations (40 CFR Part 146) on injection wells, can minimize the risk of groundwater contamination from casing failures. But, the potential for fracturing the confining stratum above the disposal zone is uncertain and requires further study. The EPA proposes restricting injection pressures to preclude this possibility.

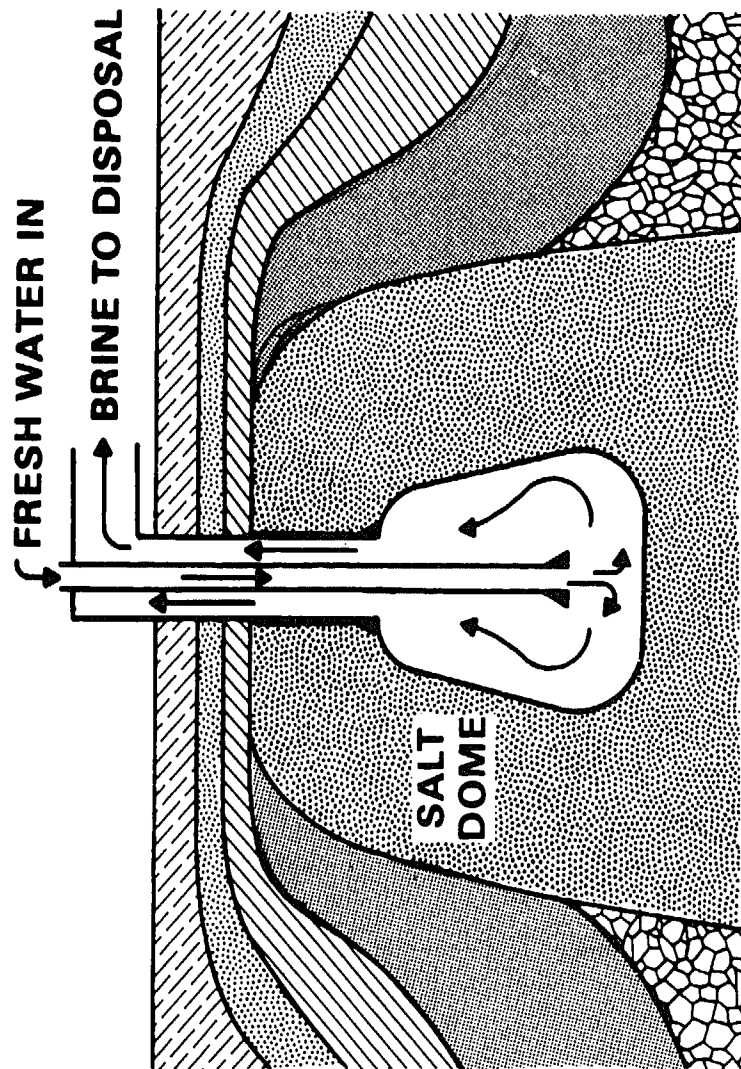


FIGURE 5. Solution Mining a Salt Cavity

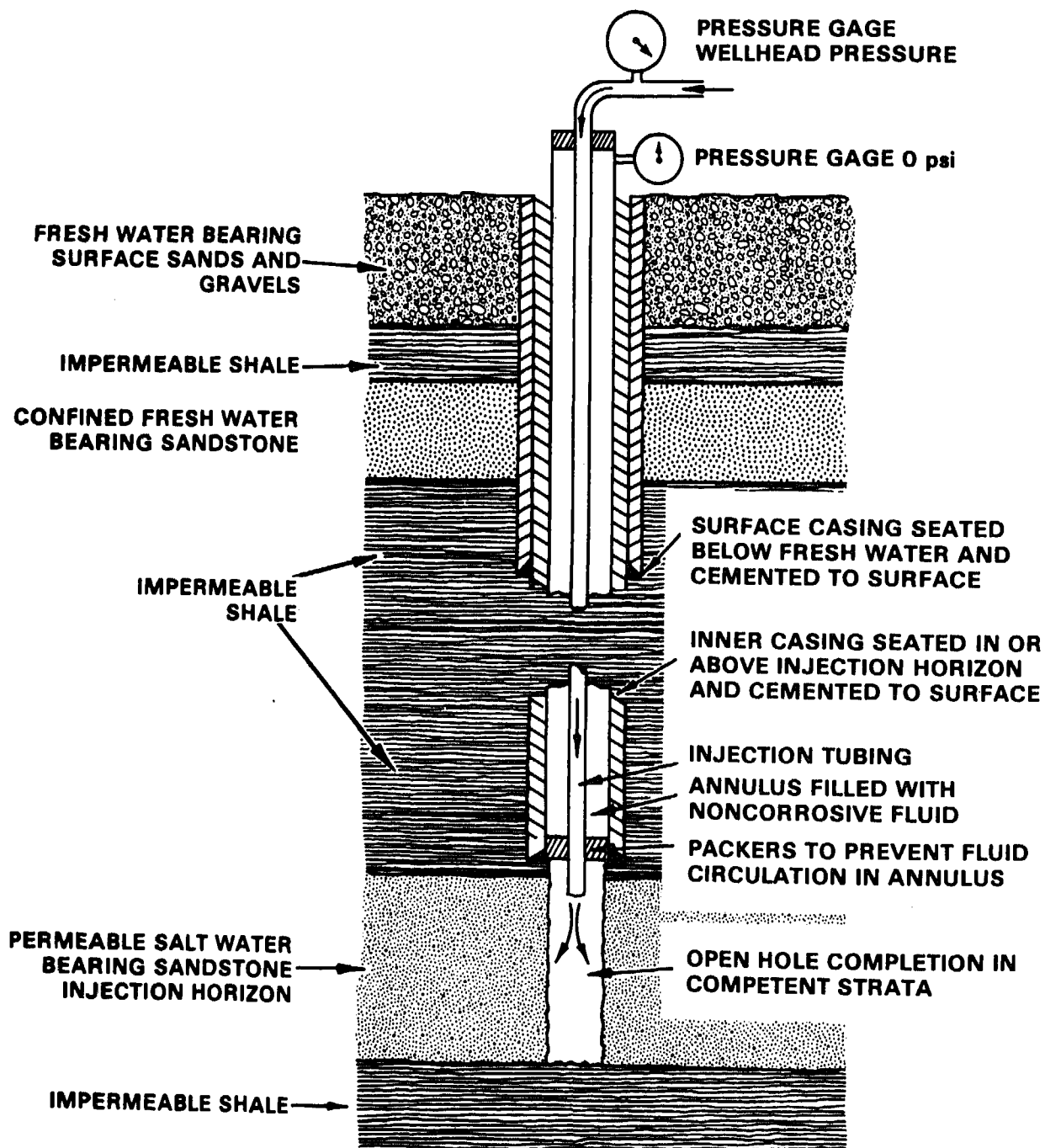


FIGURE 6. Injection Well for Underground Waste Liquid Disposal (Reference 2)

issues.

Impacts on geologic structures

The major potential impacts are associated with the stability of the reservoir against collapse or closure, as these could result in subsidence of the land overlying the reservoir. Subsidence has been known to occur as the result of underground mining operations and from the pumping out of groundwaters and petroleum without sufficient recharge efforts. Besides changing the topography, subsidence may cause subsurface rock formations to buckle and fracture, opening up cross-aquifer contamination pathways.

Control of subsidence relies upon prevention of reservoir failure. This requires greater understanding of the behavior of rock materials under stresses produced in CAES operations. This understanding will enhance proper site selection and the determination of limits on operating parameters to preclude failure. As mentioned previously, the Reservoir Stability and Design Criteria Program at PNL is addressing these issues. The long-term fate of an abandoned CAES site will also have to be determined, and appropriate decommissioning practices developed.

Aesthetics and land use considerations

It would appear that, at least for uncompensated systems, the surface facilities of a CAES plant are no more unsightly than conventional peaking plants. A compensating water reservoir, if subject to large variations in surface level, might be considered an aesthetic nuisance. Aquifer storage plants would have a large grid of surface collection lines, but these could possibly be buried.

Noise problems associated with a CAES operation are possible. Because the compressor and turbine do not operate at the same time, sound intensity should be lower than a conventional plant. However, the CAES plant will operate most of the day in either a compression or generation mode. Since noise is perceived as a logarithmic function of the sound intensity, the overall perception may be that the CAES plant is a greater nuisance than the conventional plant.

CAES plants generally require more land area than conventional plants. Aquifer storage in particular requires a greater area due to the large number of injection wells. One conceptual design for a 600 MW plant estimated land needs of 1200 acres. For compensated cavern storage, the water reservoir may require several hundred acres. Even without a surface reservoir, the potential for subsidence may limit development of land near the plant.

the successful long term operation of a CAES technology, and investigation of environmental concerns and the overall investigation of technical and operational factors will be a synergistic process. The CAES Environmental Control Concerns Program was established at PNL to ensure that environmental control planning is an integral part of technology development. In this way, the early implementation of CAES can be facilitated.

CAES technology draws from a number of established technologies, such as mining, underground storage of gas, subsurface waste disposal, and turbine generation of electricity. Thus, environmental control practices developed with these technologies are applicable to CAES environmental concerns in many cases. Other concerns, which result from the stresses placed on the environment due to the unique operating characteristics of CAES, require the development of adequate control strategies. A research program has been initiated to achieve this development.

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Chairman: William Savage

Co-Chairman: Charles Grua

AN OVERVIEW OF THE DEPARTMENT OF ENERGY'S METEOROLOGICAL EFFECTS OF
THERMAL ENERGY RELEASE (METER) PROGRAM

Alan M. Rubin, U.S. Department of Energy, Energy Technology
Harry Moses, U.S. Department of Energy, Environment
David Eissenberg, Oak Ridge National Laboratory

The objective of the Meteorological Effects of Thermal Energy Release (METER) Program is to develop methods and a data base to assess the atmospheric effects of heat and moisture releases from large nuclear and fossil energy generating facilities. The METER program, which began initially in 1976, is a long-term study jointly supported by the Advanced Systems and Materials Production Division and the Division of Biomedical and Environmental Research of DOE to establish the impact of heat dissipation from large energy generating facilities on the atmosphere and methods of mitigating such impacts. Included in the program are effects from mechanical and natural draft cooling towers, as well as cooling ponds and canals. The atmospheric effects which are of interest include precipitation modification, fogging and icing, multiple plume interactions, drift deposition, shadowing, and others.

The METER program is subdivided into three coordinated elements: (1) field studies, (2) physical modeling, and (3) mathematical modeling and involves five contractors - Oak Ridge National Laboratory (ORNL), Battelle Pacific Northwest Laboratory (PNL), Argonne National Laboratory (ANL), Penn State University, and the Rand Corporation.

Current studies are primarily directed towards field studies at operating plants. ORNL is carrying out a statistical precipitation study over a several year period at the 3200 MWe Bowen plant in Georgia utilizing a dense raingage network around the plant to determine to what extent normal rainfall patterns are affected by thermal emissions from natural draft cooling towers. A second field study, by PNL, is analyzing drift deposition and transport from mechanical draft cooling towers. Penn State University is conducting airborne measurements of velocity, temperature, and drift within plumes from a natural draft tower. ANL is conducting a study of the effects of cooling ponds on the environment.

In the area of mathematical modeling, the Rand Corporation is conducting numerical model studies to provide a better understanding of the effects on weather phenomena from cooling tower heat releases.

PNL is conducting physical model experiments of mechanical draft cooling towers in order to better understand the phenomena of plume interactions between adjacent cooling towers.

by

Robert A. Paddock and John D. Ditmars

Argonne National Laboratory

The efficacy of the disposal of waste heat from electric power generation by means of once-through cooling systems was examined in the context of water quality standards and guidelines for thermal discharges. The ranges of water temperature standards and mixing zone requirements were determined for rivers, lakes, estuaries, and coastal waters. Cooling-water effluent characteristics were assumed for generic 500 MW and 1000 MW fossil and nuclear power plants. Various modes of once-through cooling water disposal from each of the generic plants were examined in terms of general characteristics of each of the receiving water types. The focus of the examination of the disposal modes, surface and submerged discharges, was the likelihood that a given disposal mode could be effected without violation of the temperature and mixing zone standards for the given receiving water type. The results of model studies and of prototype measurements of thermal plume behavior were employed to determine generalized and schematic behavior of surface and submerged discharges into the various types of receiving waters. General guidelines were produced that indicated, for a given type of plant, a given discharge mode, and a given type of receiving water body, the opportunity for once-through cooling water discharge within the given temperature and mixing zone requirements. For example, a surface discharge from the generic 500 MW fossil plant into a river may meet temperature and mixing zone standards if the surface area of the 5F isotherm must be less than the area of a circle of 1000 ft radius. However, if the added requirement that the mixing zone must be less than 25% of the total cross-sectional area of the river is imposed, only a few rivers with large flows would be eligible to receive such discharges. Similar assessments have been made for all other combinations of plant, discharge, and receiving water types.

ENHANCING ENVIRONMENTAL QUALITY THROUGH THE USE OF
INTEGRATED COMMUNITY ENERGY SYSTEMS

by

Peter F. Donnelly, Argonne National Laboratory
and

Isiah O. Sewell, U.S. Department of Energy

The concept of Integrated Community Energy Systems (ICES) is more than a comprehensive energy management concept applied at the community level. It seeks the most appropriate combination of energy supply system and energy conserving community design to meet energy requirements of a particular community. The ICES concept includes a broad spectrum of technologies that meet energy

The overall energy efficiency in these systems is maximized by integrating the energy system with community or building design considerations. Integration of the energy supply system with community land uses and activities eliminates many point sources of emissions. In addition, the fuel conversion efficiency of ICES reduces the fuel required to meet given electric and thermal loads thereby reducing the quantity of emissions currently associated with meeting the same size electric and thermal loads from traditional energy supply sources.

This paper presents comparisons of emissions for communities of varying sizes served by ICES and for the same communities when served by traditional energy supply systems.

ACCOMPLISHMENTS IN THE DEPARTMENT OF ENERGY PROGRAM ON ADVANCED
CONCEPTS FOR DRY AND DRY/WET COOLING

B. M. Johnson

Battelle Pacific Northwest Laboratories

The Dry Cooling Enhancement Program at PNL has been focused on the development of technology and the initial planning (including the evaluation of the justification) for a large-scale test of an advanced dry/wet cooling concept. The overall program objective has been to develop technology to relieve the water shortage anticipated in many sections of the country through encouraging the use of dry cooling of power plants. The development of systems which are less costly, with respect to operating penalties as well as capital, and the transfer of this technology to the commercial market were seen to be essential in order to have any impact on the national problem of growing competition for existing water supplies. The system selected for large scale testing is one which uses ammonia to transfer the waste heat from the turbine to a dry cooling tower and is enhanced by two different ways of incorporating evaporative cooling. One uses a conventional cooling tower close coupled to a water-cooled ammonia condenser, the other uses water evaporated from the surface of the dry tower over which it flows.

This paper reports on the five areas of the DCE program which constituted the total thrust.

Studies of the anticipated need for dry cooling and the payoff from a successful demonstration of an improved system.

Evaluation of existing technology to identify areas in which improvements would have major impact.

Development of a consensus among various elements of the utility industry as to the wisdom of proceeding with a large scale test and the structuring of a program and a funding base to carry out the test.

This program has been coordinated with the EPRI program in water conservation; particularly with an independent study of the ammonia system conducted by Union Carbide Corp./Linde Division. The design and construction of the large scale test itself will be funded by EPRI, based on the conceptual design outlined in this paper.

WASTE HEAT MANAGEMENT IN THE ELECTRIC POWER INDUSTRY:
ISSUES OF ENERGY CONSERVATION AND STATION OPERATION
UNDER ENVIRONMENTAL CONSTRAINTS

D. R. F. Harleman et al.,
Massachusetts Institute of Technology

This paper focuses on issues of cost, conversion efficiency and environmental impacts associated with the condenser cooling systems of large steam-electric power plants. Emphasis is placed on several alternatives to the use of conventional open cycle cooling or wet cooling towers. Particular issues which have been addressed include the effect of replacement energy costs on optimal cooling system size (especially for dry towers), the development of a quasi-steady representation of the transient response of cooling systems with large thermal inertia (e.g. cooling ponds), and the effect of stream standards on the operation and penalty costs of supplementary cooling systems. Furthermore, various cooling systems have been compared at a hypothetical site and the results have been used, along with data on cooling water availability, to deduce conclusions regarding differences in cooling costs which result from varying environmental controls.

J. C. Bentz, United Engineers and Constructors
J. L. Sonnichsen, Hanford Engineering Development Laboratory
Frank Moore, Cornell University

This paper describes three studies in support of the DOE heat dissipation effort. A study of an improved heat transfer surface by Curtiss-Wright has shown substantially less cost for dry cooling towers; a power plant water data information system at REDL is described, and the Cornell University program on cooling tower wind effects is discussed, together with some possible modification which may have less wind effect.

USE OF WASTE HEAT FROM NUCLEAR POWER PLANTS

Mitchell Olszewski, ORNL

Oak Ridge National Laboratory

A review of the Oak Ridge National Laboratory (ORNL) investigations of the use of waste heat from nuclear power plants is given including an evaluation of the best ways this can be successfully accomplished. A demonstration greenhouse which is being built at TVA's Brown's Ferry Nuclear Power Station is discussed for which background heat exchange R&D was accomplished at ORNL. Pilot operation was jointly conducted with TVA. Recent analysis and experiments with aquaculture are discussed.

David Eissenberg
Oak Ridge National Laboratory

ABSTRACT

The objective of the Meteorological Effects of Thermal Energy Releases (METER) Program is to develop methods and a data base to assess the atmospheric effects of heat and moisture releases from large nuclear and fossil energy generating facilities. The METER program, which began initially in 1976, is a long-term study jointly supported by the Advanced Systems and Materials Production Division and the Office of Health and Environmental Research of the Department of Energy. Included in the program are effects from mechanical and natural draft cooling towers, as well as cooling ponds and canals. The atmospheric effects which are of interest include precipitation modification, fogging and icing, multiple plume interactions, drift deposition, shadowing, and others.

The METER program is subdivided into three coordinated elements: (1) field studies, (2) physical modeling, and (3) mathematical modeling and involves five contractors - Oak Ridge National Laboratory (ORNL), Battelle Pacific Northwest Laboratories (PNL), Argonne National Laboratory (ANL), Penn State University (PSU), and the Rand Corporation.

Current studies are primarily directed towards field studies at operating plants. ORNL is carrying out a statistical precipitation study over a several year period at the 3160 MWe Bowen plant in Georgia utilizing a dense raingage network around the plant to determine to what extent normal rainfall patterns are affected by thermal emissions from natural draft cooling towers. A second field study, by PNL, deals with drift deposition and transport from mechanical draft cooling towers. Penn State University is conducting airborne measurements of velocity, temperature, and drift within plumes from a natural draft tower. ANL is conducting a study of the effects of cooling ponds on the environment.

In the area of mathematical modeling, the Rand Corporation is conducting numerical model studies to provide a better understanding of the effects on weather phenomena from cooling tower heat releases.

PNL is conducting physical model experiments of mechanical draft cooling towers in order to better understand the phenomena of plume interactions between adjacent cooling towers.

"Nuclear Energy Center Site Survey-1975" (NUREG-0001), which contained a thorough analysis of available data regarding the effects of existing power plant atmospheric cooling systems (cooling towers and cooling ponds) on the atmosphere and also of analogous large natural and manmade heat releases comparable to those of the proposed nuclear energy centers. Because of a perceived lack of sufficient information to make adequate judgments from available data on the potential impact of energy centers on the atmosphere, along with the conclusion that significant impacts may occur based on the analysis of the analogs, the study recommended a substantial program of theoretical and observational research to provide a guide to the evaluation of heat dissipation systems and their climatic effects.

The METER program is jointly supported by the Department of Energy's Advanced Systems and Materials Production Division (Energy Technology) and the Office of Health and Environmental Research (Office for Environment). Program coordination is provided by Oak Ridge National Laboratory. In 1977, the program name was changed to METER to reflect the broader concern of DOE for the effects of heat releases from large energy generating facilities including those from fossil energy sources.

The objective of the METER program is to develop suitable methodology and supporting data for predicting the nature and magnitude of meteorological effects resulting from the release of heat and moisture from cooling towers and ponds which may have adverse environmental consequences. The effects identified as being of current concern include:

- o drift transport and deposition,
- o precipitation augmentation,
- o ground-level temperature and humidity increases,
- o shadowing,
- o fog and icing,
- o interaction between cooling tower and stack plumes,
- o triggering of severe storms (including tornadoes, hailstorms, etc.), and
- o chemical transformations within cooling tower and stack plumes.

The intent in developing the predictive methodology is to provide regulatory agencies, utilities, and consulting firms with improved methods for assessing the environmental impact of future power plant atmospheric cooling systems. The program will also provide sufficient information to assist utilities in the layout, spacing, and location of possible future large energy centers so as to minimize the potential adverse impacts.

*Originally the Atmospheric Effects of Nuclear Energy Centers (AENEC) Program.

either of a case study type, and active power plants, or studies of long duration.

Mathematical modeling. Theoretical analyses provide insight into the mechanisms responsible for specific effects and provide the basis for developing mathematical models that describe and predict the interactions of plumes and the atmosphere. Mathematical models which describe the observed behavior of plumes (either in field studies or in physical modeling experiments) while retaining theoretical validity are useful in extrapolating those results to larger sizes or different atmospheric conditions.

Physical modeling. Laboratory-scale experiments are useful in simulating certain aspects of the interactions between heat and moisture plumes and the ambient atmosphere. Experiments of three general types are carried out:

1. those which examine one feature of the interaction process with the objective of increasing the understanding of the fundamental mechanisms involved;
2. those which extrapolate from simple systems for which mathematical analyses are available to more complex systems, such that the mathematical analyses can be extended to predict these more complex interactions;
3. those which simulate actual proposed atmospheric cooling systems in order to predict specific effects at those sites.

A number of support activities are carried out to provide assistance to coordinate the preceding elements. These include the compilation of power plant inventories, the organizing of workshops and technical sessions at professional meetings, and the coordination of METER activities with similar programs not part of the METER program.

There are five participants currently carrying out work in support of the METER program. These include Argonne National Laboratory (ANL), Oak Ridge National Laboratory (ORNL), Battelle Pacific Northwest Laboratories (PNL), Pennsylvania State University (PSU), and the Rand Corporation. A brief description of each of these participants' programs, including recent accomplishments and future plans, follows. For additional information, the reader is referred to METER annual progress reports (1, 2)* and other references listed at the end of this paper.

*Numbers in parentheses indicate references at the end of this paper.

moisture released from the towers are negligible compared with those released by a thunderstorm, cooling tower plumes could serve as a triggering mechanism to upset instabilities in the atmosphere and thus disturb storm patterns and modify precipitation.

The analysis of precipitation modification is a difficult task and requires a thorough understanding of natural precipitation variability. The distribution of precipitation with respect to both time and space is dependent in a complex manner on the interactions between the large-scale motions of air masses and localized perturbations at the earth's surface caused, for example, by changes in elevation, thermal sources and sinks, and sources of condensation nuclei. Except for specific locations where one perturbation is sufficiently strong so as to cause obvious changes in the precipitation patterns, detection and quantification of the effect requires careful statistical analysis.

Oak Ridge National Laboratory is conducting a study of the potential precipitation modification effects induced by cooling tower plumes (3-5). Plant Bowen of the Georgia Power Company was chosen as a test site. The 3160 MWe coal-fired plant is situated about 40 miles northwest of Atlanta, Georgia, and has four natural-draft cooling towers. Composed of four units (the first unit commenced operation in October 1971 and the fourth in November 1975), it is one of the largest plants in the world using cooling towers as the sole cooling method. The water vapor discharge from the four towers is estimated at about 40,000 gal/min (2500 liters/sec).

The precipitation study, which consists of two parts, is aimed at determining whether the heat, moisture, and/or condensation nuclei emitted by a large fossil power plant cooled by natural draft cooling towers is sufficient to modify the precipitation patterns in the region around the plant. The first part of the study is a statistical analysis of climatological data recorded by the National Weather Service (NWS) at its regular stations and the stations of the Cooperative Network. The second part is a field study involving operation of a specially installed dense network of recording raingages and windsets (Figure 1) within 15 miles of the plant.

The main purpose of the first study is to utilize already available climatological data taken prior to and after the plant's initial operation in order to form a comprehensive picture of rainfall patterns and variability for the preoperational and postoperational periods. Comparisons of results for the two periods yield possible indications of plant induced effects. This study also served in laying the groundwork for the field study in the identification of the appropriate target areas and the determination of the raingage network density and shape.

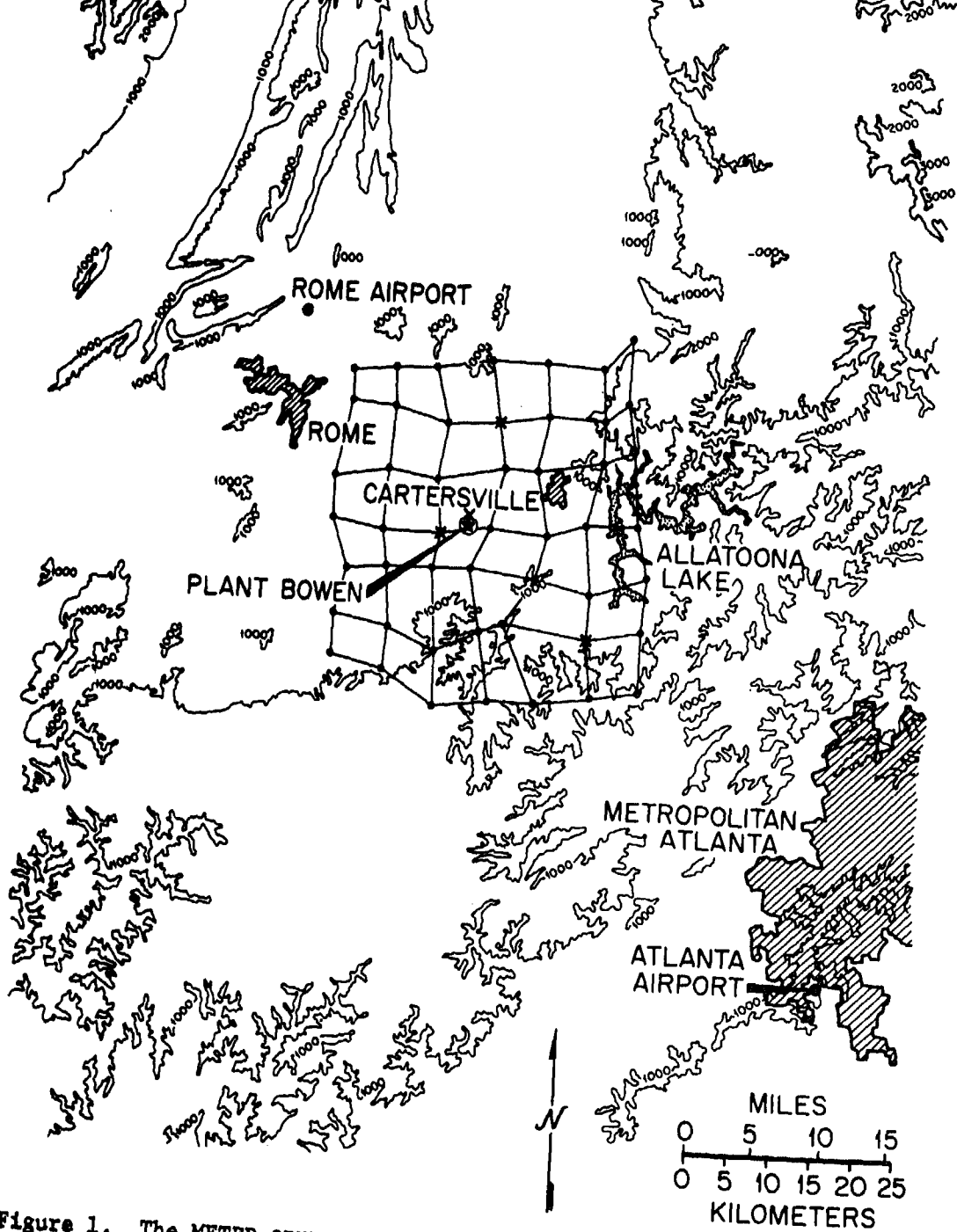


Figure 1. The METEOR-ORNL precipitation network around Plant Bowen.

which depict lines of equal precipitation (in inches) for one storm.

The network is expected to operate for five years which is believed sufficient time to provide definitive qualitative and quantitative estimates of the plant's potential effect on rainfall.

Cooling Tower Plume Measurements

A comprehensive program of plume measurements is being carried out by Pennsylvania State University (6,7). For the past few years, PSU has studied the characteristics of cooling tower and stack plumes of the Keystone Power Generating Station near Indiana, Pennsylvania. A picture of the plumes on one day is shown in Figure 3. Measurements have been made at the ground as well as in the air. A 680E Aero Commander containing a high quality comprehensive instrumentation system was used to obtain measurements aloft. More than 35 separate sensors have been integrated into the airborne system to make special measurements of atmospheric turbulence, aerosols, and radiation in addition to conventional measurements of temperature and wind. Aerosol sampling is accomplished through the use of an isokinetic decelerating probe. Aerosol sampling instrumentation includes a condensation nuclei counter for measuring total Aitken particle concentration, an optical particle counter sensitive only to particles larger than $0.3\mu\text{m}$ diameter, and a cascade impactor onto which carbon coated electron microscope screens were placed. A quantitative method, developed at Penn State for the analyses of individual sulfate particles using a transmission electron microscope allows for the identification and sizing of particles of the sulfate aerosol collected. For ground-based measurements Pennsylvania State University has available an acoustic sounder which is used to sense remotely plume turbulence characteristics.

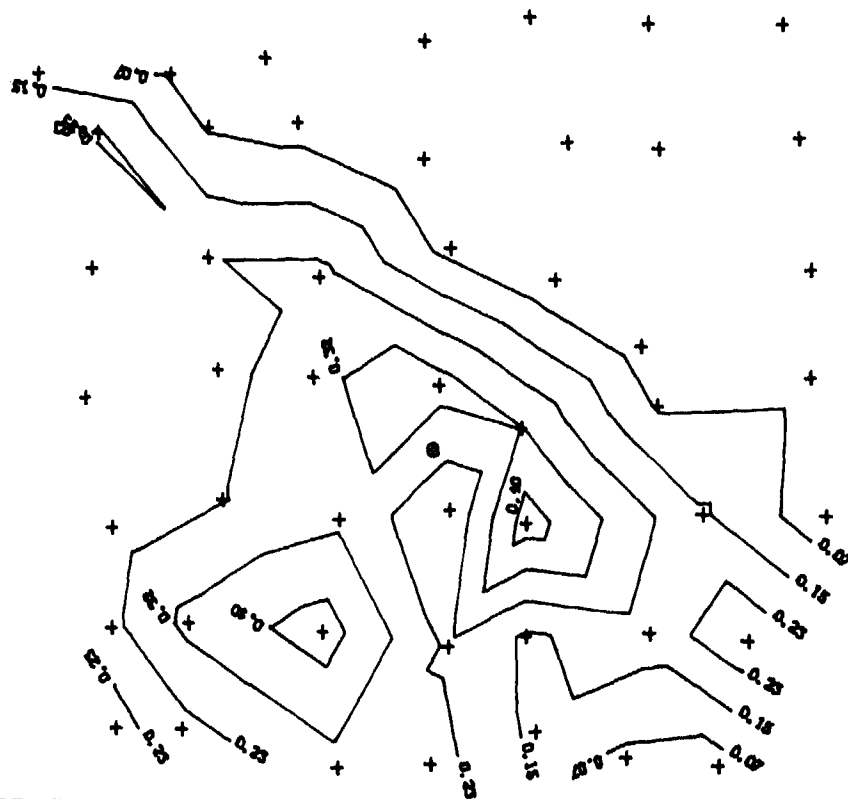
The aircraft was used to obtain plume measurements of air motions, heat, and moisture. A sample of the vertical velocities as measured in the course of a plume traverse is shown in Figure 4. The horizontal axis has a high resolution equivalent to about two meters.

The air circulation within the plume has also been obtained from the aircraft measurements. Downdrafts have been observed to occur on the outer edges of the plume. These downdrafts carry with them drift droplets thus providing the means by which the droplets are separated from the plume itself.

The aircraft has also been used for measuring the aerosols downwind of the power plant stack. Very interesting results have been obtained as is shown in Figure 5. During sunny days (flights 1 and 2) the concentration of small sulfate particles increases with plume travel time thus the ratio of particles greater than $0.3\mu\text{m}$ to the total Aitken particle concentration decreases with travel time. During cloudy conditions and high humidity (flight 4), the growth of pre-existing particles exceeded the formation of

STORM NO. 9

3/25/78



MAX. PRECIP. - 0.44 IN.
MIN. PRECIP. - 0.00 IN.

STORM BEGAN DAY 25 AT 1
STORM ENDED DAY 25 AT 2
STORM DURATION 5.0 HRS

STORM TYPE - OCCLUDED F
SURFACE WIND DIRECTION
UPPER AIR WIND DIRECTION
PLANT BOMEN POWER OUTPUT

Figure 2. Computer-generated contours of precipitation (in in.) for Storm No. 9 in the METER-ORNL precipitation network.

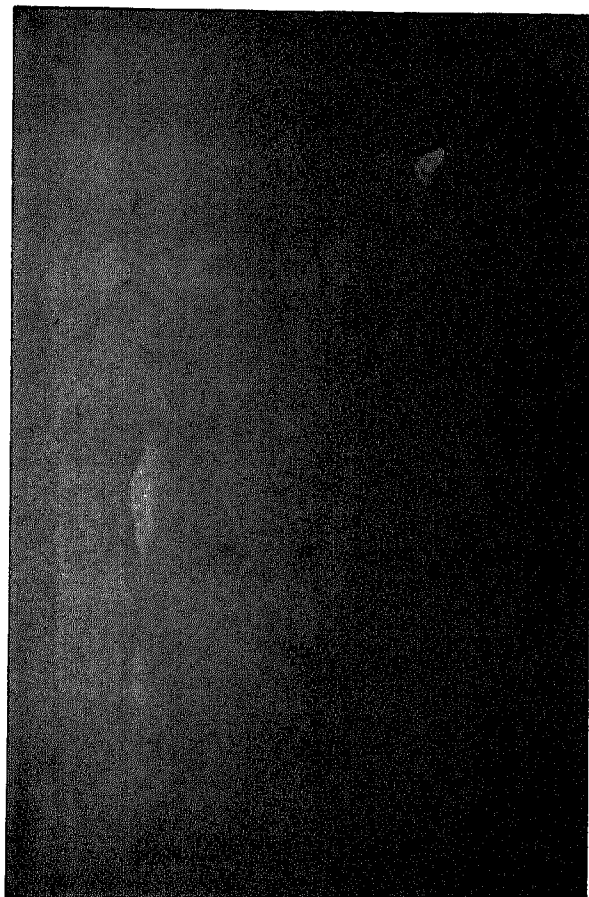


Figure 3. Cooling tower plumes from the Keystone Power Generating Station.

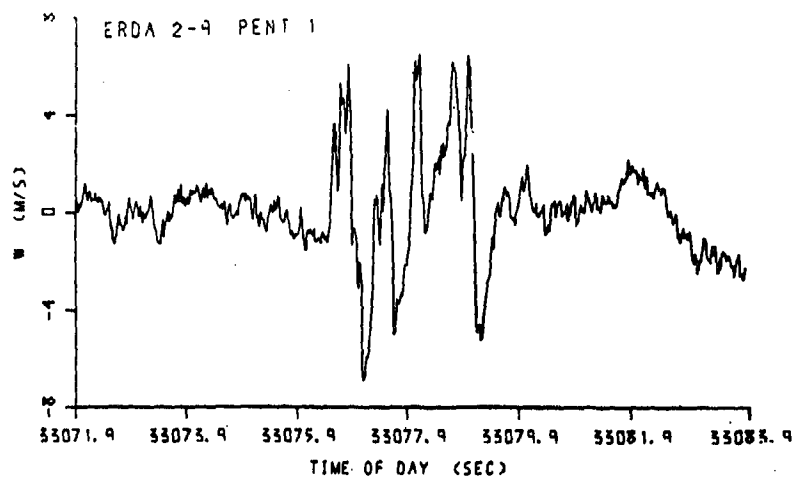


Figure 4. Pennsylvania State University aircraft data showing the profile of vertical velocity (m/sec) measured during a flight penetration through a plume.

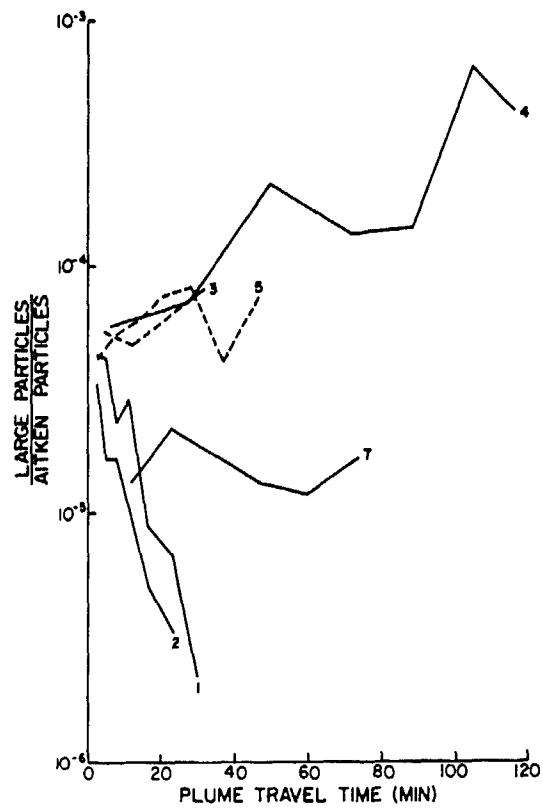


Figure 5. Aircraft measurements of particle sizes downwind of Keystone power plant stack.

the turbulence and wake effects produced by the tower itself.

Drift Deposition From Mechanical-Draft Cooling Towers

Drift consists of entrained droplets of water and accompanying dissolved and suspended solids which are discharged from wet cooling towers within the plume of warmed moisture-laden exhaust air. As the plume loses buoyancy by mixing with ambient air, the drift droplets tend to settle out of the plume, ultimately depositing on the terrain downwind of the cooling towers. The distribution and concentration of deposited drift, and particularly its solids content, are of major concern in assessing the impact of locating power plants using cooling towers near agricultural or residential areas. Although mathematical models based on theoretical considerations are used to predict the drift deposition (8,9), there are insufficient data from field measurements to validate these models.

A recently completed field study by Battelle Pacific Northwest Laboratories (10) of drift deposition at the Pittsburg Plant (a 2030 MWe oil-fired power plant located near San Francisco, California) was aimed at providing new measurements of drift deposition from mechanical draft cooling towers. Unit 7 of the plant, which is rated at 720 MWe, is cooled by two rectangular mechanical draft cooling towers. Units 1-6 employ once through cooling. The field study involved two weeks of intensive measurements of the emission from the cooling towers, the local meteorological conditions affecting transport of the drift, and the distribution of deposited drift on the ground downwind of the plant. Support for the measurement of drift emission characteristics was provided by the Fossil Fuel and Advanced Systems Division of the Electric Power Research Institute. A total of eight runs were carried out, and the results are currently being analyzed and compared to available mathematical models.

Cooling Pond Studies

Both natural and manmade ponds have been used to dissipate waste heat from power generating stations. Although other forms of heat dissipation such as natural or forced draft cooling towers are frequently used, cooling ponds may offer advantages in certain situations. For example, a cooling pond represents a more diffuse source of heat and water vapor than a cooling tower. It is, therefore, less likely to trigger mesoscale atmospheric phenomena such as cloud formation, precipitation or vorticity enhancement. The primary factor concerning the use of cooling ponds in energy centers is the vertical flux of sensible and latent heat into the atmosphere since it is this flux which (a) determines the operational efficiency of the heat dissipation system, (b) controls the pond water temperature to which biological systems are exposed, and (c) governs the formation of steam fog.

the eddy correlation method of flux measurement in developing and verifying accurate formulations of the fluxes of heat and water vapor from cooling ponds. The vertical flux of any variable is directly related to the time-averaged product of the fluctuations about the mean of the variable of concern and the simultaneous fluctuation values of vertical velocity. For example, the vertical flux of heat is directly related to the time-averaged product of temperature and vertical velocity fluctuations. In the use of this method the time constant of the sensors must be properly matched and measurements must be made within the constant flux layer.

Most of the studies to date by the ANL group have taken place at Dresden, Illinois at a cooling lake of the Commonwealth Edison Company. This lake is divided into five ponds of which the one closest to the plant outlet has received the most attention. A photo of the meteorological tower in this pond is shown in Figure 6. Work has also taken place over a small artificial pond ten square meters in area at the ANL Meteorology Site.

During the early work it was necessary to obtain information on the rate of growth of the internal boundary layer. This was investigated in order to obtain accurate measurements by the eddy correlation technique. It was found that the surface roughness of the Dresden pond, which is an important parameter in cooling pond studies, is about one-half of that over the ocean for the same wind speed.

In order to complete a comprehensive cooling pond study it is necessary to test the results of the Dresden program at a variety of locations. Further, it is planned to conduct a series of feasibility studies of different methods for identifying and monitoring the plume downwind of existing ponds.

Physical Modeling

The collocation of many cooling towers at one site (as, for example, at potential power parks) may lead to complex plume interactions among adjacent cooling towers, with station structures, local facilities, and with the surrounding terrain. The analysis of these phenomena by mathematical modeling or field experiments is often impractical.

The purpose of the physical modeling studies is to investigate the dynamics of cooling tower plumes in the near field of the power generation site. Of specific interest are the changes in plume characteristics for various ambient, tower operating, tower siting, and local topographic conditions.

Data from physical modeling experiments can be useful in the evaluation and verification of mathematical models. Although it may be difficult or impossible to simulate all meteorological conditions, studies can be conducted in modeling tests at relatively low cost, whereas field experiments

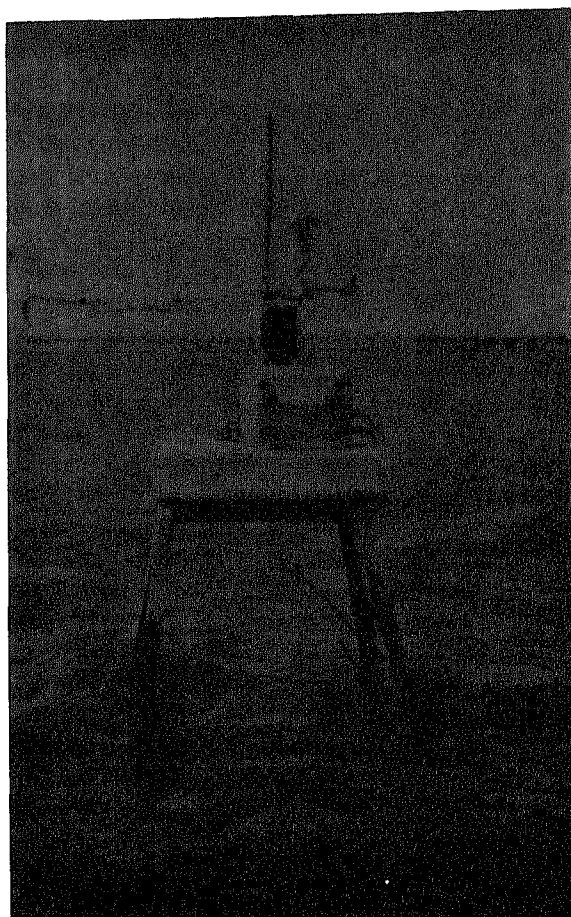


Figure 6. Meteorological tower at Dresden cooling pond.

...ity of siting, design and operating conditions. Mechanical draft towers were selected for this effort because the plume is discharged at relatively low elevation (less than 25 m above the ground), and therefore terrain and other effects will be larger than if tall natural draft towers (150 m) were used. Three tasks are currently being pursued:

- o simulation of multiple mechanical-draft tower plume behavior over a wide variety of operating conditions in flat terrain;
- o investigation of topographical effects on single- and multiple-plume dynamics using simple trapezoidal solids;
- o development of techniques for extrapolating the results from the above two tasks to complex terrain.

Data from measurements in the flume which include local temperature and velocity fields, are analyzed to determine quantitative relationships between plume dynamics and tower orientation, spacing, operating characteristics and topographic conditions.

Results to date suggest that optimal siting of cooling towers, particularly multiple towers, is a task requiring knowledge of ambient wind history, multiple plume dynamics, and tower operating conditions. Tower wake effects exert a heavy influence on plume dynamics and interaction. For example, highly buoyant plumes from mechanical draft towers will follow Briggs' single tower relationship (15). However, wake effects will cause considerable deviation for less buoyant plumes in moderate winds. Also, the plume merger dynamics represented in Briggs' multiple plume rise enhancement formulation are dwarfed by more significant plume/wake dynamics for the cases investigated.

MATHEMATICAL MODELING

Although the emphasis on the METER program has recently been on the collection and analysis of data from field studies, several analytical studies have also been undertaken to predict the meteorological effects of power plant heat and moisture releases. The development of mathematical models of the effects of interactions of plumes with the atmosphere parallels and supports field programs in providing the basis for predicting the environmental effects of cooling towers. Some of these efforts are discussed briefly below.

The Rand Corporation has concentrated its efforts in numerical modeling in two areas. One of these had as its objective the development of criteria for predicting precipitation of snow from cooling tower plumes. Actual observations of snowfall from natural draft cooling tower plumes have been reported in the literature (16). The Rand study (17) summarized conditions

sensible and latent heat and cloud formation using numerical simulation. In three experiments, a given amount of energy was regarded either as all sensible heat, all latent heat, or half sensible/half latent. It was found that with equal heat flux densities, sensible heat was much more likely to initiate convective circulations and anomalous cloudiness than latent heat. This suggests that where the potential for cloudiness is a factor, wet cooling towers would be preferable to dry towers.

In a recently completed study by Battelle Pacific Northwest Laboratories (19), the mathematical basis for predicting rainfall enhancement due to scavenging of cooling tower condensate was developed. Based on previous analyses of scavenging of solid particulates by rainfall, the mathematical analysis permits the prediction of the incremental amount of rain expected directly beneath a cooling tower plume during a natural rain as a function of wind, rainfall rate, and plume parameters. For a large natural draft cooling tower releasing 1.7×10^7 g/sec of condensate, plume centerline rainfall enhancement is predicted to be measurably high at downwind distances between 100 m and 1 km for moderate wind speeds and rainfall rates. PNL is planning a field study in 1979 to check the results of this theoretical analysis.

Numerical models of cooling ponds have been developed by ANL (19,20) to provide surface temperatures and surface fluxes over water as functions of space, time, plant output, and meteorological conditions. These models are designed to serve the dual-purpose of describing performance characteristics in a manner suitable for use in plant operations and providing information on the input of heat and moisture into the atmosphere for meteorological effects evaluations. A new method for the prediction of the occurrence of steam fog over cooling ponds was developed by ANL. This "Fog Excess Water Index" is basically a measure of the supersaturation which results when air at ambient temperature and humidity mixes with air which is saturated at surface temperatures.

Analytical model development has also been carried out by Pennsylvania State University. A cooling tower model has been designed to predict the length of the plume, its thickness, rise, and trajectory. It was found that the model is highly sensitive to wind speed. Under low wind conditions, the PSU model consistently underestimated plume length, overestimated plume thickness, and predicted trajectories correctly. In high winds it overestimated plume length, underestimated its thickness, and no consistent results could be determined for trajectories. The best estimates for plume length were obtained in the medium speed range.

Two other METER-related studies are described in References 22 and 23. In addition, the Air Resources Atmospheric Turbulence and Diffusion Laboratory

ture releases from hypothetical power parks.

CONCLUSION

The comprehensive METER program described in this paper to characterize the environmental effects of large power plant heat rejection systems will provide an insight into the sighting and impact of power generation on the environment.

ACKNOWLEDGEMENTS

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ABSTRACT

The efficacy of the disposal of waste heat from electric power generation by means of once through cooling systems was examined in the context of the physical aspects of water quality standards and guidelines for thermal discharges. The ranges of water temperature standards and mixing zone requirements were determined for rivers, lakes, estuaries, and coastal waters. Various modes of once through cooling water disposal from each of four generic plants were examined in terms of general characteristics of each of the receiving water types. The focus of the examination of the disposal modes, surface and submerged discharges, was the likelihood that a given disposal mode could be effected within the restrictions of the thermal standards for the given receiving water type. The results of prototype measurements and of model studies of thermal plume behavior were employed to determine generalized and schematic behavior of surface and submerged discharges into the various types of receiving waters. General guidelines were produced that indicated, for a given type of plant, for a given discharge mode, and for a given type of receiving water body, the opportunity for once through cooling water discharge within the given temperature and mixing zone requirements. For example, a surface discharge from a generic 500 MW fossil plant into a river may meet mixing zone standards, if the surface area of the 5 F° isotherm must be less than the area of a circle of 1000 ft radius. However, if the added requirement that the mixing zone not encompass more than 25% of the total cross-sectional area of the river is imposed, only a few rivers with large flows would be eligible to receive such discharges. Similar assessments have been made for all other combinations of plant, discharge, and receiving water types. While specific guidelines are provided for each receiving water type, the general conclusion reached is that submerged multiport diffusers provide the greatest opportunity to meet thermal standards in all environments.

1. INTRODUCTION

The demand for electric power in the United States has doubled every ten years since 1945. Electric power demands are expected to increase steadily in the foreseeable future, although rates of increase of demand may decrease due to energy conservation policies and declines in population and industrial growth rates. Present and near-future electric power generation will be accomplished primarily at central steam-electric generating stations. Such stations convert thermal energy, derived from the combustion of fossil fuels or from a nuclear reactor, into electrical energy with overall thermal efficiencies of 30-40%. As a result of these efficiencies, 1.5-2.3 units of waste heat are produced for each unit of electric energy generated. As significant improvements in thermal efficiency or the introduction of alternative methods of central station electric generation are not expected in the near future, the disposal or beneficial utilization of large quantities of waste heat will be an abiding aspect of central station electric energy generation.

combinations of these systems). Associated with each disposal technology are economic, energy, and environmental costs. The study reported here focused on an aspect of the environmental control technology for once through cooling systems. In once through cooling systems, water is drawn from a nearby water body (river, lake, reservoir, estuary, or coastal region), passed through the power plant condensers, and returned directly to the water body at an elevated temperature. No attempt is made here to compare the total costs (economic, energy, and environmental) of once through cooling to costs of other systems, although studies by others¹ indicate that, in many cases, the construction, operating, and energy costs of once through cooling systems are less than those for other disposal technologies.

Quantification of the costs of environmental impacts of waste heat disposal systems, and indeed of the impacts themselves, is often elusive. Consequently, general conclusions regarding the efficacy of once through cooling systems in terms of their environmental impacts are not possible. Environmental assessments of once through cooling systems are usually made on a case-by-case basis. The matters of primary concern in such assessments are the effects of the impingement of organisms on the cooling water intakes, of the entrainment of organisms into the condenser system, of the passage of organisms through the thermal plume created in the receiving water body, and of the local warming of the water body in the vicinity of the discharge. All of these issues are highly dependent on site-specific conditions and intake and discharge designs. However, the two latter concerns are addressed indirectly in water quality standards and guidelines by means of general restrictions on the temperature elevations and on the physical extent of such elevations permitted. The focus of this study was investigation of the feasibility of employing once through cooling systems that do not exceed these restrictions on the physical behavior of the thermal plumes created.

For this study, the restrictions on the temperature elevations above ambient water temperatures and the sizes of the mixing zones in which those elevations may be exceeded were enumerated for the various potential receiving waters for waste heat disposal: rivers, lakes, estuaries, and coastal waters. Typical cooling water flow rates and power cycle temperature elevations of the cooling water were determined for generic 500 MW and 1000 MW fossil and 500 MW and 1000 MW nuclear electric power plants. Given the restrictions on plume behavior in the receiving water types and the cooling water discharge characteristics, analyses were made for each combination of receiving water and plant type to determine, *in general terms*, the feasibility of effecting once through cooling within the physical environmental constraints. Both surface and submerged discharge structures were examined in terms of the results of prototype field data augmented by the results of physical and mathematical model studies, and guidelines were developed for either the limiting environmental conditions or the discharge structure size and configuration required. Again, the thrust of the analyses was the formulation of general conclusions regarding the efficacy of once through cooling systems for a variety of water environments, as site specificity precludes detailed conclusions.

and standards be developed. The National Technology Advisory Committee (NTAC) to the Secretary of the Interior developed water quality criteria and published their recommendations in April 1968.² The NTAC also set forth recommendations for temperature standards for water bodies receiving waste heat discharges. They recommended a maximum permissible temperature rise above naturally existing temperatures of 5F° (2.8C°) for streams and rivers and 3F° (1.7C°) for lakes. They also recommended that cold-water fisheries (trout and salmon waters) not be disturbed. In marine and estuarine environments, they recommended that monthly maximum daily temperatures at a site not be raised by more than 4F° (2.2C°) in the winter (September - May) or by more than 1.5F° (0.8C°) in the summer (June - August). In addition, the NTAC recommended that mixing zones, within which temperature standards are not met, should be as small as possible and should be determined on a case-by-case basis.

In 1972, Congress adopted the Federal Water Pollution Control Act Amendments. The Act sets the goal of eliminating the discharge of pollutants into navigable waters by 1985; waste heat is specifically included as a pollutant. Section 316(a) of the Act, however, applies specifically to the disposal of waste heat and authorizes the Administrator of the EPA to impose alternative effluent limitations on a case-by-case basis if the "protection and propagation of a balanced indigenous population of shellfish, fish and wildlife" in and on the receiving water body can be assured.

The purpose of this study was to examine the various types of discharge concepts available for once through cooling systems and to determine the circumstances under which each type might be acceptable. Because the question of acceptability is clearly site dependent and must be addressed on a case-by-case basis, some general criteria had to be selected and used to determine acceptability. Any such general criteria can only be used as guidelines or for initial screening purposes, because they cannot take into account the variety and distribution of aquatic organisms present at a particular site. Compliance or lack of compliance with temperature and mixing zone standards is often included in the development and evaluation of any argument concerned with the acceptability of thermal discharges. In fact, guidelines for the preparation of 316(a) exemption documents specify inclusion of predictions of the behavior of the thermal plumes. Therefore, specific temperature and mixing zone standards were used in this study to compare, contrast, and evaluate the performance of various types of discharges in various types of receiving waters.

Water quality standards vary from state to state, however many are patterned after the recommendations of the NTAC. These temperature standards were selected for use in this study. Mixing zone limitations were not specified explicitly by the NTAC, but recommendations to be considered when establishing a mixing zone were set forth. When mixing zones are defined, they are often stated in terms of surface areas or areas equivalent to circles of specified radii. The specified radii typically range from 300 ft (91m) to 1000 ft (305m). The corresponding areas range from 6.5 acres ($2.6 \times 10^4 \text{ m}^2$)

3. DISCHARGE FLOW RATES AND DILUTION REQUIREMENTS

The power cycle used by steam-electric power plants requires that a portion of the total heat energy generated by the power plant be rejected as waste. Some of this waste heat is dissipated directly to the atmosphere, either through the smoke stack or through other in-plant losses, but most must be dissipated through the cooling water system. For a typical fossil-fueled plant, about 1.4 units of waste heat energy are delivered to the cooling water system for each unit of electric energy generated. In the case of a nuclear plant, lower operating temperatures and pressures result in 2.0 units of waste heat per unit of electric energy generated. It is evident that a nuclear power plant produces about 45% more waste heat than a fossil plant of the same generating capacity.

The cooling water flow rate, Q_p , and the temperature rise, ΔT_o , due to the addition of the waste heat are related to the generating capacity of the power plant, C , by:

$$Q_p \Delta T_o = KC$$

where:

$$K \approx 0.33 \frac{\text{m}^3 \text{ C}^\circ}{\text{MW s}} \quad \text{for fossil plants, and}$$

$$K \approx 0.47 \frac{\text{m}^3 \text{ C}^\circ}{\text{MW s}} \quad \text{for nuclear plants.}$$

The actual temperature rise depends on the particular power plant design, but a survey of over 50 power plants yielded an average value of 10.0 C° (a value that appears to be typical of new, larger power plants).

Over the next 5-10 years, new generating capacity is expected to be made up of an approximately equal mix of nuclear and fossil-fueled plants, primarily in the 500-1000 MW range. In order to compare and contrast the efficacy of various types of once through cooling systems, four typical large generating units, each with an initial cooling water temperature rise of 10.0 C° were considered. These four plants and an estimate of the cooling water flow rate requirements are listed in Table 1.

In order that the once through cooling system of steam-electric power plants meet the temperature standards discussed above, or indeed any temperature standards, the heated effluent must mix sufficiently with the ambient receiving water within some specified mixing zone to reduce the excess temperature below the specified maximum. It is assumed that the temperature of the ambient receiving water is at approximately the same temperature as the cooling water at the system intake, and that the temperature of the cooling water is elevated by about 10.0 C° (18.0 F°), then the temperature standards impose a minimum dilution that must be attained. This dilution can be

500 MW - fossil	10.0	16.5
500 MW - nuclear	10.0	23.5
1000 MW - fossil	10.0	33.0
1000 MW - nuclear	10.0	47.0

estimated by the ratio of the temperature rise across the condenser to the maximum temperature rise allowed at the outer edge of the mixing zone. Table 2 lists the dilution requirements for the various types of receiving waters corresponding to the temperature standards discussed earlier.

4. DISCHARGE TYPES

There are almost as many types of once through cooling discharge designs as there are power plants. Intake and discharge configurations are usually developed for each power-plant site to accomodate local shoreline and bottom topography and naturally occurring currents and tidal flow. However, the various discharge designs employed can be divided into three basic categories: shoreline surface discharges, single-port submerged discharges, and submerged multiport diffusers. Shoreline surface discharges have long been used by power plants due to low construction costs and ease of maintenance and servicing. In recent years more stringent thermal standards and a change in the philosophy of disposing of waste heat have brought about more interest in the use of submerged discharges. Submerged discharges tend to have higher outfall

Table 2. Typical Temperature Standards and Dilution Requirements

Water Body	ΔT_{\max} (F°/C°)	Dilution
Streams and Rivers	5/2.8	3.6
Lakes	3/1.7	6.0
Estuaries and Marine Coastal Waters		
Winter	4/2.2	4.5
Summer	1.5/0.8	12.0

Prediction of the behavior of both surface and submerged discharges of waste heat is required for the design and assessment of once through cooling water systems. Predictive models, both mathematical and physical, for these purposes have been developed over the past 15 years. Physical (hydraulic scale) models are usually developed for site-specific conditions, and while providing some information of general value, often are operated for limited ranges of parameters. In most cases analytical and numerical models, while providing useful insights into the behavior of and design guidance for discharge systems, have been developed for idealized discharge and receiving water conditions. Models typically cited for surface discharges include those of Pritchard^{3,4}, Stolzenbach and Harleman⁵, and Shirazi and Davis⁶; for submerged discharges, those of Fan and Brooks⁷, Hirst⁸, Koh and Fan⁹, and Shirazi and Davis¹⁰; and for shallow water diffusers, those of Adams¹¹, Jirka and Harleman¹², and Almquist and Stolzenbach.¹³ Reviews of these and other mathematical models have been reported by Policastro and Tokar¹⁴, Benedict et al.¹⁵, Dunn et al.¹⁶, and Jirka et al.¹⁷

Many simplifications and approximations are used in the development of models such as those mentioned above. Therefore specific predictions must be used with caution unless the model has been verified under similar circumstances by comparison with some sort of experimental or field data. Prototype field data collected at power plant sites where various types of once through cooling systems have been used were reviewed for this study. These data were augmented with physical and mathematical model results and used to assess the efficacy of generic discharge design concepts. The four typical power plants and the dilution and mixing zone requirements discussed above were used as a framework to determine the circumstances under which once through cooling may be an acceptable alternative for waste heat disposal. One or two general parameters characteristic of the discharge design or the receiving water body were used to qualify the conclusions.

5. RIVERS

The major characteristics that identify a water body as a river, for the purposes of once through cooling systems, are (1) unidirectional flow and (2) limited lateral extent. Limited lateral extent implies that both banks of a river may influence the behavior of the thermal effluent, although the degree of influence clearly depends on the size of the thermal discharge and geometry of the river. River flow rates generally vary in time, especially with season. Controlled rivers or run-of-the-river reservoirs may undergo significant daily, and even hourly, fluctuations in flow, particularly when controlled for hydropower purposes. The availability of river flow for dilution can clearly be a limiting factor with regard to the use of once through cooling water systems on rivers. Other factors that influence the behavior of thermal discharges in rivers are: channel geometry, lateral and vertical variations in velocity, temperature stratification, and ambient turbulence.

$$Q_R \geq \frac{KC}{\Delta T_{\max}}$$

For a maximum temperature excess of 5 F° (2.8 C°) as suggested by the NTAC for rivers or a dilution of 3.6 for the generic plants, a 500 MW fossil plant would require a river flow rate of at least 59 m³/s, a 500 MW nuclear plant 85 m³/s, a 1000 MW fossil plant 119 m³/s, and a 1000 MW nuclear plant 169 m³/s. In practice, however, complete mixing is not attained (of even allowed, as discussed below), and larger minimum river flow rates are needed.

Historically, shoreline surface discharges were the prevalent form of once through cooling water system employed on rivers before the present temperature standards were promulgated. The principal concern of the designers of these discharges was the avoidance of recirculation of the heated effluent to the cooling water intakes. Thus, shallow, low-velocity outfall channels were used to confine the heated effluent to the near-surface region and to avoid vertical mixing. Then, skimmer walls were employed in front of the intakes to effect selective withdrawal of deep, cool water.

Prototype scale field data from measurements of cooling water plume behavior at three different river discharges were reviewed. These discharges were for the TVA's Widows Creek plant¹⁸ on the Tennessee River near Stevenson, Alabama, the Vermont Yankee Nuclear Power Station¹⁹ on the Connecticut River at Vernon, Vermont, and the Monticello Nuclear Power Generating Plant²⁰ on the upper Mississippi River near Monticello, Minnesota. The measurements at these plants cover the ranges of several important governing parameters, but the data are too limited to establish detailed relationships among the characteristics of the surface discharge and of the river. For typical low-velocity, surface, shoreline outfalls, however, these data and results of model studies suggest that the plant cooling water discharge, Q_p , is the most important parameter. The area of the mixing zone is primarily influenced by the cross-sectionally averaged river velocity, U_R . Recall that, while other details of the discharge and the river flow are clearly important in specific cases, only gross parameters for establishing guidelines are sought. The data are limited, but they suggest that in order for surface, shoreline discharges to meet the more restrictive mixing zone surface area requirement of $2.6 \times 10^4 \text{ m}^2$ (area equivalent to a circle of 300 ft radius), a 500 MW fossil plant ($Q_p = 16.5 \text{ m}^3/\text{s}$) would require a river velocity of about 0.1-0.4 m/s and a 1000 MW nuclear plant ($Q_p = 47.0 \text{ m}^3/\text{s}$) would require a river velocity of about 1.4-1.6 m/s. It also appears that the less restrictive mixing zone requirement of $2.9 \times 10^5 \text{ m}^2$ (area equivalent to a circle of 1000 ft radius) could easily be met by a 500 MW fossil plant for a river velocity less than but on the order of 0.1 m/s, while a 1000 MW nuclear plant would require a river velocity of less than but on the order of 0.3 m/s.

In a river, the cross-sectional area of the mixing zone is often restricted to less than 25% of the cross-sectional area of the river. By the time a dilution of 3.6 is reached, the flow velocity in the plume will be

average, the cross-sectional area of the plumes is approximately $2.8 Q_p/U_R$. If it is required that this area be less than 25% of the total cross-sectional area of the river, this places a restriction on the total flow rate of the river, Q_R . In particular, the flow rate of the river must be at least about 11 times the discharge flow rate of the plant. This river flow rate is about three times that which would be required if rapid, complete mixing with the entire river could be attained. The river flow rates for the four typical power plants investigated are listed in Table 3. Only the major river systems in the U.S. have flow rates which are consistently this large. For example, the monthly 20-year low flow exceeds $340 \text{ m}^3/\text{s}$ (12,000 cfs) only in the Mississippi, Missouri, Ohio, and Tennessee Rivers, the Columbia and Snake Rivers, and the St. Lawrence, Niagara, Detroit, St. Clair, and St. Mary's Rivers. The Mobile and Alabama Rivers, the Apalachicola River, and the Sacramento River can be added to this list, if rivers with monthly 20-year low flows greater than $170 \text{ m}^3/\text{s}$ (6000 cfs) are considered.²¹ Clearly, surface discharges, in the general sense discussed here, have limited efficacy as a once through cooling water control technology.

Submerged, multiport discharges provide the opportunity for more rapid mixing and, therefore, may require smaller river flows to meet the same thermal standards than a power plant with a surface shoreline discharge. Typically, a submerged, multiport diffuser in a river consists of a pipe extending into the river along the bottom perpendicular to the direction of flow. The cooling water is discharged at relatively high velocity through several ports in the pipe, usually in the downstream direction. If a diffuser can be built across the width of the river so that essentially the full flow of the river passes over the diffuser and if the diffuser can be designed to produce rapid, full mixing with the entire river flow, then the minimum river flow required to meet the temperature standards discussed above would be 3.6 times the flow rate of the plant. A criterion for full mixing of the thermal effluent just downstream of the diffuser was developed by Argue and Sayre.³⁶ Application of this criterion to the four power plants under consideration indicates that a minimum discharge velocity is required, but those values do not appear to constrain multiport diffuser designs measurably. For example, the discharge velocity required for a 1000 MW nuclear plant on a river of width 10 m is at least 3 m/s -- with smaller required values for wider rivers. The minimum river velocity required to avoid upstream spreading of the heated effluent on the surface was investigated following the analysis of Jirka and Harleman.¹² For the case of a river with a mean depth of 3 m, the minimum river velocity required to counter upstream spreading is about 0.13 m/s. Therefore, design of a multiport diffuser that produces full mixing at minimum river flow rates seems feasible in most cases. If mixing is sufficiently rapid, the surface area restrictions (the mixing zone) would probably not be a limitation. A river flow rate somewhat larger than this would probably be needed due to the additional requirement that less than 25% of the cross-sectional area and volume flow of the river be blocked by the mixing zone.

Table 3. Estimated River Flow Rates to Achieve Temperature Standard Within Mixing Zone (Dilution of 3.6) of 25% of Cross-Sectional Area of the River, Except as Noted

Type of Plant	Plant Flow Rate m^3/s	Shoreline Surface Discharge	Required River Flows, m^3/s				Multipoint Diffuser (relaxation)
			Multipoint Diffuser (fully mixed) ^b	1/4 River Width		$U_R/U_o = 0.1$	
				Multipoint Diffuser	Multipoint Diffuser		
500 MW, fossil	16.5	182	59	206	134	94	
500 MW, nuclear	23.5	259	85	294	190	134	
1000 MW, fossil	33.0	363	119	413	267	188	
1000 MW, nuclear	47.0	517	169	588	381	268	
		(11) ^a	(3.6) ^a	(12.5) ^a	(8.1) ^a	(5.7) ^a	

^aMultiple of plant cooling water discharge.

^bIgnoring 25% restriction, full mixing allowed.

^cDiscounting areas surrounding jets in 25% calculation.

less than 4 times $3.6 Q_p$ and depends on the relative magnitudes of the river and diffuser discharge velocities. Adams¹¹ has analyzed the case of diffusers without confining banks, and application of his results to the case of the "1/4-width" diffuser indicates that: (1) when the river velocity is 0.2 of the discharge velocity, the river flow required for a dilution of 3.6 is about $12.5 Q_p$, and (2) when the river velocity is 0.1 of the discharge velocity, the required river flow is only about $8.1 Q_p$ (see Table 3). Thus, it is likely that a diffuser occupying 25% of the river width can be designed to meet temperature standards. But, it should be noted that such a diffuser will induce flows over it that are greater than 25% of the river volume flow.

An alternate view of the "25% restriction" is that some of the water surrounding individual jets from a multiport diffuser is at temperature elevations less than that maximum set by the standards and is, therefore, not part of the mixing zone. Such an interpretation would permit the length of the diffuser pipe to occupy more than 1/4 of the width of the river. Application of the results of Parr and Sayre²² from model studies of the diffuser for the Quad-Cities Nuclear Power Station on the Mississippi River to the diffusers studied here indicates that a diffuser can be designed that extends across the full river width and only requires a river flow of 1.6 times that required for full mixing to meet temperature standards and the relaxed interpretation of the 25% cross-sectional encroachment restriction (see Table 3).

While the efficacy of surface discharges as a control technology for waste heat disposal appears limited, the application of submerged multiport diffuser systems for this purpose seems feasible for a larger range of rivers. Depending on the interpretation of the mixing zone requirement of encroachment of the thermal plume on less than 25% of the river cross-sectional area and flow, river flow rates required to meet standards range from 12.5 to as low as 5.7 times the plant cooling water discharge rate.

6. LAKES

The major characteristics used to identify a water body as a lake for the purposes of once through cooling are (1) large, essentially unlimited, lateral extent; (2) currents which are variable in both magnitude and direction; and (3) no significant tidal variation of currents or water depth. Large lateral extent implies that only the shore boundary near the power plant affects the behavior of the discharge and the resulting thermal plume. For the lakes considered, the heat added by the power plant is small compared to the total heat budget of the lake; therefore, the measurable physical effect of the discharge is confined to the vicinity of the power plant and does not extend over a significant fraction of the entire water body. Impoundments for which this is not true should be treated as cooling ponds or cooling lakes. The variability of the ambient currents implies that, although they clearly will affect the dispersal of the waste heat, they cannot be relied

periods ranging from hours to months, depending on heating, lakewide circulation, and local and lakewide meteorological conditions.

The previous discussion of typical temperature standards in lakes and typical discharge temperatures indicates that a dilution of at least 6.0 is required for lakes and that that dilution must be accomplished within a mixing zone with a surface area of $2.6 \times 10^4 \text{ m}^2$ (equivalent to a circle with 300 ft radius) to $2.9 \times 10^5 \text{ m}^2$ (1000 ft radius circle) to meet typical thermal standards on a lake.

Until the early to mid 1970's, most power plants sited on large lakes used shoreline surface discharges to dispose of waste heat. The outfalls typically consist of open channels which terminate at or near the shoreline. The depth of the channel at the point of discharge is usually limited by the water depth at that point to 1.5-4.0 m. Discharge velocities are small, usually in the 0.5-1.0 m/s range. The resulting discharge jets, characterized in fluid mechanical terms, often have small discharge densimetric Froude numbers (2-8).

Because surface discharges on lakes have been used for a number of years, a considerable amount of data from field measurements exists in the form of horizontal isotherm areas as a function of excess temperature and depth. Forty-seven sets of thermal plume data from surface discharges at nine different power plants on the Great Lakes were reviewed²³, with particular attention given to surface areas within isotherms corresponding to physical dilutions of 6.0 or excess temperature ratios of 0.17. The range of cooling water discharge rates for these data was 3.2-69.1 m^3/s . A relationship was sought among the surface area of the isotherm corresponding to the dilution of 6.0, the discharge characteristics, and the receiving water characteristics. The simple expression $A_{6.0}/Q_p = 3.15 \times 10^4 \text{ s/m}$ was found from the data, where $A_{6.0}$ is the area in m^2 within the isotherm corresponding to a dilution of 6.0, Q_p is the plant cooling water discharge in m^3/s , and the standard deviation of the numerical value is $1.70 \times 10^4 \text{ s/m}$. This expression, of the form proposed by Asbury and Frigo²⁴, is hardly satisfactory from a fundamental viewpoint as the near-field behavior of the plume clearly depends on the details of the discharge geometry. However, no scaling parameter related to the discharge could be found to improve the correlation beyond that of using the plant flow rate. Also, the behavior of the plume in the region of dilution 6.0 is very much dependent on far-field or ambient processes. Examination of data for conditions of fixed discharge characteristics reveals considerable variations in plume areas apparently due to variations in lake currents and stratification, although field data on the ambient characteristics are too sparse to permit meaningful correlations. Reviews¹⁶ of mathematical models for surface discharges indicate that they have been unable to predict consistently isotherm areas in the far field. Finally, for the purpose of this generalized assessment of once through cooling water technologies, the simple relationship between plant discharge and isotherm areas is probably sufficient.

very unlikely that the more stringent mixing zone area restriction of $2.6 \times 10^4 \text{ m}^2$ (300 ft radius circle) could be met by such a plant. It appears that plants, fossil or nuclear, with capacities greater than 500 MW would not be able to meet thermal standards for lakes by means of conventional shoreline surface discharges as the once through cooling water technology.

Because shoreline surface discharges fail to meet the temperature mixing zones standards for lakes in many cases, recently constructed and planned, large-capacity power plants on lakes have employed submerged discharges for the disposal of waste heat. Submerged discharges have generally higher velocities than surface discharges and, because of discharge at depth, result in substantial dilution of the effluent by the time it reaches the water surface. The increased dilution due to mixing results in correspondingly smaller mixing zones at the surface where mixing zone standards usually apply. The configuration of submerged discharge systems vary, but, in general terms, they can be put in two categories: single structures with a few discharge openings and multiport diffusers with numerous discharge ports.

Submerged single structures seem to be unique and generalizations about their performance are few. Of course, as is the case with all submerged discharges, increased relative submergence (ratio of the water depth above discharge openings and the characteristic opening size) leads to increased plume dilution at the surface. Two submerged single structure type discharges at which field measurements of the thermal plumes have been made are the Zion Nuclear Power Station^{25,26} and the D. C. Cook Nuclear Power Plant²⁷, both on Lake Michigan. The Zion plant has two units and two similar discharges ($50 \text{ m}^3/\text{s}$) with small relative submergences of about 5 and discharge velocities of about 2.4 m/s. Eight surveys of the thermal plume when only one unit was operational indicated that the minimum surface dilution (i.e., the dilution corresponding to the maximum surface excess temperature) is only 1.4-2.0. The asymmetry of the discharge with respect to the shore parallel lake currents was evident in the plume measurements that showed surface areas corresponding to a dilution of 6.0 to be $6-8 \times 10^4 \text{ m}^2$ when the discharge was in the same direction as the ambient current and $1-6 \times 10^5 \text{ m}^2$ when the discharge was into an on-coming current. Measurements when both units were operational demonstrated that significant interactions can occur between the adjacent thermal plumes. This type of discharge meets, under certain circumstances, the lake thermal standards previously discussed above, but its ability to do so depends on ambient lake currents that are highly variable. The D. C. Cook Unit 1 discharge ($46 \text{ m}^3/\text{s}$) consists of two slots with discharge velocities of about 4.1 m/s and relative submergence of about 8. Measurements indicate that minimum surface dilutions are 2.2-3.3 and that surface areas corresponding to a dilution of 6.0 are $9-20 \times 10^4 \text{ m}^2$ for most surveys, although surface areas of about $1 \times 10^6 \text{ m}^2$ were measured on two occasions. As in the case of the Zion discharge, the size of the mixing zone depends upon ambient currents and can be variable, occasionally larger than mixing zone standards for lakes.

Multiport diffusers employ many discharge openings or ports that are

tunnel oriented approximately parallel to the shoreline in 9-10 m of water. The discharge velocity is about 4.3 m/s and the relative submergence is about 12. Field surveys²⁸ of the thermal plume indicate that the minimum surface dilution, based on the highest observed surface temperature excess, is in the range of 6-14. Although there is, again, apparently significant dependence on ambient receiving water conditions, the initial dilution induced by the multiport diffuser is such that, over a range of conditions, considerable surface dilution is achieved in close proximity to the diffuser.

Multiport diffusers appear to be the most promising method of disposing of large quantities of waste heat from once through cooling systems on large lakes. Because the dilution attained at the surface above a multiport diffuser depends on water depth, port diameter, port orientation, number of ports, diffuser length (or port spacing), and ambient currents, several design options are available to achieve surface dilutions of 6.0. Calculations²³ of buoyant jet behavior and diffuser dynamics for ranges of discharge parameters for the four generic power plants demonstrate that dilutions of 6.0 can probably be obtained, for even the largest discharge, in water depths as low as 5 m provided the diffuser is sufficiently long (maximum length about 350 m). The dilution performance depends also on the site-specific ambient current structure and on the configuration and orientation of the diffuser with respect to those currents. For example, in the case of a "tee" diffuser with port discharges oriented offshore, approximately perpendicular to shore-parallel currents, ambient currents may result in decreased dilution due to interference between adjacent jets. Application of an analysis, similar to that by Adams and Stolzenbach²⁹, to this situation indicates that large lake cross currents of 0.25 m/s may require increases in "tee" diffuser length of 60% or more over that required for small or negligible current designs to maintain a dilution of 6.0. Other diffuser configurations, such as "staged" diffusers, may provide suitable designs in large-current environments -- as indicated in the following section on estuaries. (Adams and Stolzenbach²⁹ review the advantages, disadvantages, and trade offs among several types of submerged diffusers for shallow water.) It appears that multiport diffusers can, barring any pathogenic site-specific characteristics, provide an adequate means of meeting thermal standards on lakes.

7. ESTUARIES

Estuaries are water bodies exhibiting the effects of both saline tidal waters and freshwater runoff. Physical and biological processes in estuaries are diverse. Circulation is often a complex function of seasonally varying river inflow and of ocean tides modified by geometric features such as islands, peninsulas, embayments, and tidal flats. Water density structure varies with both salinity and temperature. The wide diversity of characteristics makes it difficult to specify general features which identify an estuary. For the purposes of this study, the major characteristics which are used to identify

followed again by large currents in the opposite direction. This reversal of flow continually returns to the discharge site some fraction of the waste heat discharged during a previous part of the tidal cycle.

Prediction of the fate of waste heat from a power plant sited on an estuary is extremely difficult due to the complexities described above. Analytical models cannot usually handle the complicated geometries and flow patterns often present at such sites. Physical (hydraulic scale) models usually cannot be made large enough to operate over several tidal cycles to include the effect of returning heat. Even if the model were large enough, hydraulic scaling laws do not allow both near-field effects, such as jet induced mixing, and jet-current interaction, and far-field effects, such as buoyant spreading, natural turbulent mixing, and surface heat loss, to be simulated in the same physical model. The approach most often used to design thermal discharges for estuaries is to construct a physical model of the near- and intermediate-field regions and operate it over different critical segments of the tidal cycle to determine the mixing that can be expected in the vicinity of the outfall due to the discharge jet itself and the immediate interaction with the local currents. The effect of the return of heat due to current reversals is then treated analytically based on the results of field measurements involving the tracking of dye releases over several tidal cycles.¹⁷ These complicated design procedures make it difficult to develop a detailed, yet general, treatment of the thermal discharge at an estuarine site. Therefore, many of these factors are not treated in the following discussion.

Conventional shoreline surface outfalls (open channels) do not appear to be acceptable alternatives for once through cooling for large power plants on estuaries due to the large initial dilution which is required. (See Table 2.) In order to operate on a year-round basis, a thermal discharge must be designed to meet the more restrictive summer standards. Based on the same field data and procedure discussed in Section 6 on surface discharges in lakes, an estimate can be made of the ratio of the surface area corresponding to a dilution of 12, A_{12} , to the discharge flow rate of the power plant, Q_p . The data available in this case are more limited because often the field surveys did not extend to the small excess temperatures ($\approx 0.8^\circ\text{C}$) which correspond to a dilution of 12. Values of this ratio, A_{12}/Q_p , from as small as $2 \times 10^4 \text{ s/m}$ to larger than $10 \times 10^4 \text{ s/m}$ were observed. A reasonable estimate appears to be $7 \times 10^4 \text{ s/m}$ based on the original curve drawn through the data by Asbury and Frigo²⁴. Based on this value for A_{12}/Q_p , only power plants with capacities of less than 10 MW could meet the mixing zone limitation of $2.6 \times 10^4 \text{ m}^2$ (equivalent to a circle of 300 ft radius) and only plants of less than 100 MW could meet the limitation of $2.9 \times 10^4 \text{ m}^2$ (1000 ft radius circle) for the typical summer temperature standard. Power plants with capacities of 500-1000 MW would require mixing zones 10-100 times larger and, therefore, conventional surface shoreline outfalls would probably not be acceptable.

only reduces the size of the mixing zone during a given phase of the tidal cycle, but also tends to reduce the excess temperature associated with heat returned to the site during subsequent tidal phases and, therefore, reduces its effect on the plume. Again, as in the case of a river site, the diffuser cannot extend across the entire estuary so that a zone of passage, free from large excess temperatures, is maintained for fish and other aquatic organisms.

A co-flowing diffuser, such as is often considered for riverine applications, will usually not be appropriate in an estuary where the flow is bi-directional. When the estuary flow is in the same direction as the flow of the diffuser discharge, or when the flow is large, such a diffuser may perform satisfactorily. However, when the flow is small and opposed to the direction of the discharge, the effective dilution will decrease sharply.²⁹

A "tee" diffuser, such as has been used in some lake applications, could be considered for an estuary, if only weak tidal currents are present. This type of diffuser has its main axis essentially parallel to the shoreline with the ports oriented in the offshore direction. Estimates of the length of the diffuser and the size and number of ports necessary to obtain the required dilution have been made.²³ These estimates show that, in estuaries, except for high velocity discharges (≥ 4 m/s) in deep water (≥ 10 m), long diffusers (500-1000 m) would be required by a 1000 MW nuclear power plant to attain a minimum surface dilution of 12. This estimate is based on discharges into a quiescent receiving water body. In an estuary, tidal currents will be present and, in general, will be along the axis of the "tee" diffuser. Because of interactions between jets, such currents will tend to reduce the effective dilution attained. Based on an empirical correlations suggested by Adams and Stolzenbach²⁹, it can be shown that even a small cross current (≈ 0.1 - 0.2 m/s) would require a 10-20-fold increase in the length of the diffuser or possibly even completely negate the possibility of designing a "tee" diffuser which would result in a dilution of 12. These results indicate that the "tee" concept is probably not appropriate in estuaries where large dilutions are required in the presence of substantial tidal cross currents.

An alternative diffuser design concept is that of the alternating diffuser on which discharge ports are directed normal to the diffuser pipe or tunnel in both directions so that no net horizontal momentum is introduced. Such a diffuser would be oriented across a portion of the estuary, perpendicular to the tidal flow. When no ambient currents are present, the dilution is governed by density driven exchange flow¹², and the dilution would actually increase in the presence of currents in either direction. An estimate of the diffuser length required to produce a dilution of 12 in the case of a quiescent receiving water can be made based on the simple analysis developed by Jirka and Harleman¹². The predicted lengths are 5-10 times larger than those for a "tee" diffuser in stagnant water. However, in the case of an alternating diffuser, currents will increase the dilution while in the case of a

coastal sites. The diffuser pipe or tunnel is oriented perpendicular to the shore and the ports are located on alternate sides of the pipe directed in the general offshore direction. A jet-type flow is induced along the axis of the diffuser in an offshore direction and water is entrained primarily from the sides. The orientation of the individual jets is such that significant interference occurs between the individual jets. Therefore, in the case of quiescent receiving waters, a significantly longer staged diffuser would be needed to attain the same dilution as a "tee" diffuser. However, staged diffusers have the distinct advantage that cross currents tend to enhance dilution rather than hinder it, in contrast to the case for a "tee" diffuser.

Almquist and Stolzenbach¹³ have carried out an approximate analysis of the behavior of staged diffusers in shallow quiescent receiving water. The results of their analysis indicate that a staged diffuser length of 4-5 times that of a "tee" diffuser would be required to attain a minimum dilution of 12, but the fact that cross currents increase the dilution attained by a staged diffuser rather than decrease it makes staged diffusers a very promising multiport diffuser design concept. Table 4 contains estimates of the length, L_0 , of a staged diffuser required to attain a minimum surface dilution of 12 for a typical 1000 MW nuclear power plant for several discharge velocities, U_0 , and receiving water depths, H .

These estimates of the required lengths of a staged diffuser are probably more conservative than necessary to meet typical thermal standards. Usually the temperature standards and, therefore, the dilution requirements must be met beyond some specified mixing zone. Thus, dilution at the edge of a mixing zone of finite areal extent at the surface is the limiting factor, not the minimum surface dilution. Estimates of the staged diffuser length needed to attain a dilution of 12 within a mixing zone of specified surface area can be made based on the Almquist-Stolzenbach¹³ analysis and the result of laboratory scale experiments at Alden Research Laboratories.³⁰ Table 4 contains such diffuser length estimates for a typical 1000 MW nuclear power plant for mixing zone surface areas of $2.6 \times 10^4 \text{ m}^2$ (equivalent to a 300 ft radius circle), designated L_1 , and $2.9 \times 10^5 \text{ m}^2$ (1000 ft radius circle), designated L_2 . These results show that significantly shorter diffuser lengths can be utilized for high velocity discharges (4-5 m/s) in receiving waters of greater than 5-m depth.

The decision as to whether once through cooling will be an acceptable method for disposing of waste heat from a steam-electric power generating station located on an estuary will have to be made on a case-by-case basis. The decision process will have to include analysis of site-specific data and may have to include laboratory scale physical model experiments to estimate the effects of complex site-specific geometric constraints and currents and field experiments to establish local heat return and flushing rates. However, it appears that at least under some circumstances, submerged multiport diffusers of reasonable length can be designed which will produce the large

H(m)	U _o (m/s)	L _o (m)	L ₁ (m)	L ₂ (m)
5.0	2.0	6,880	6,810	5,150
5.0	3.0	4,750	4,480	2,600
5.0	4.0	3,420	3,190	1,510
5.0	5.0	2,750	2,430	930
10.0	2.0	3,370	3,150	1,510
10.0	3.0	2,210	1,840	580
10.0	4.0	1,630	1,150	<150 ^a
10.0	5.0	1,290	780	<150 ^a
15.0	2.0	2,160	1,840	560
15.0	3.0	1,390	930	<225 ^a
15.0	4.0	1,000	560	<225 ^a
15.0	5.0	760	350	<225 ^a

^aThe analysis is limited to L>15H.

dilutions that are required in an estuarine environment.

8. OPEN COASTAL WATERS

Open coastal waters by their very nature offer a large sink for the disposal of waste heat. Large quantities of heat can be accommodated with little or no effect on the overall thermal regime of the water body. The only physical environmental concern is limited to the local increase in water temperature in the immediate vicinity of the outfall and possibly the impact on close-by, shallow, nearshore areas. Longshore currents which are predominantly in one direction are often present. While these currents may aid in bringing in cool dilution water, care must be taken that cooling system structures extending from the shore do not interfere with natural littoral transport. In general, open coastal waters should serve well as receiving water bodies for once through cooling waste heat discharges.

Certain regions of very large lakes such as the Great Lakes might be classified as open coastal waters. However, larger induced excess temperatures are usually allowed than in marine waters due to the larger natural temperature variations there, and the use of the Great Lakes for disposal

by the geometry of the connecting passage, especially when stratification exists.¹⁷ Complex density and current structures may require that a specific bay or inlet be treated as an estuary in terms of establishing the applicability of once through cooling. Larger bays with significant tidal flushing might be treated as open coastal waters.

An interest in using offshore waters for the disposal of waste heat has developed due to several novel concepts which can be applied to the conventional steam-electric generating process. One is offshore power generation on a floating barge or artificial island. And, another is the nuclear energy center (NEC). An offshore plant would allow the generating station to be located near the load center without requiring the dedication of large land areas which might be better utilized. A NEC is a group of many (≈ 10) large generating units located at one site. Such a center could be located somewhat inland to avoid using valuable shoreline land, and the center could use common pipes or tunnels to bring cooling water from offshore intakes and return it to offshore outfalls.³¹ The use of once through cooling by such centers rather than evaporative cooling towers would eliminate some of the disadvantages of large cooling tower installations such as large land use, decreased thermal efficiency, and local atmospheric and meteorological impacts. Deep, offshore intakes would take advantage of lower intake temperatures due to natural thermal stratification, and submerged outfalls would take advantage of increased dilution due to greater submergence.

The shallow slope of the continental shelf along the Atlantic coast of the U.S. precludes reaching very deep water. For example, the proposed Atlantic Generating Station, a floating nuclear plant, is tentatively sited about 5 km off the coast of New Jersey yet is in only about 10-12 m of water. Both surface and submerged outfalls have been considered for this installation.³² Another example is the Seabrook Station near Seabrook, New Hampshire³³ which will use a 4.0-km long intake tunnel and a 4.6-km long discharge tunnel, each 5.5 m in diameter and about 60 m below sea level. This will allow the plant to be located about 3.1 km inland of the open coast and the intakes and discharges to be located 0.9 km and 1.5 km off shore respectively. Even with the long tunnels, the discharge, proposed to be a 300-m long diffuser with a discharge velocity of 4.6 m/s, will be in only about 15 m of water. Although accessible water depths are limited along the Atlantic coast, offshore plants and/or outfalls may eliminate any effects of the thermal plume on the shallow nearshore region. The Pacific coast offers access to deeper depths within reasonable distances off shore.

As with the design of any outfall, the selection of an outfall design to be used at an open coastal site will have to take into consideration local currents and bottom topography. A large initial dilution will be required (≈ 12 for the typical summer thermal standard and typical outfall excess temperatures discussed earlier). Based on the discussion in Section 7 on estuaries, conventional surface shoreline outfalls usually will not be adequate. High velocity submerged discharges will be necessary to attain

various diffuser designs for use with units 2 and 3 (1100 MW each) at the San Onofre Nuclear Power Plant on the coast of California. They concluded that a staged diffuser design would best meet the requirements at that site. Each unit would have its own diffuser about 760 m long with a discharge velocity of 4.0 m/s. One diffuser would be in 9-13 m of water and the other, farther offshore, in 13-17 m of water.

9. SUMMARY AND CONCLUSIONS

Once through cooling water control technology has been reviewed to determine the circumstances under which forms of this technology might provide acceptable alternatives for the disposal of waste heat from large steam-electric power plants. The final determination of the acceptability of once through cooling at a particular site must be made on a case-by-case basis. Many factors enter into the evaluation process including: (1) the heat rejection rate of the plant, (2) the size and type of the receiving water body, (3) local physical characteristics of the water body, (4) the existence of other nearby sources of heat, (5) the character and distribution of indigenous populations of shellfish, fish, and wildlife, (6) the physical extent of the resulting thermal plume, (7) the impact of the thermal plume on aquatic organisms, (8) the impact of the cooling water intake on aquatic organisms, and (9) the costs and impacts of alternative waste heat disposal technologies. This study was limited to assessing the efficacy of once through cooling in terms of the restrictions on the physical extent of the thermal plume produced. Typical water quality standards and guidelines were used as a measure of the acceptability of a once through cooling system and as a means of comparing the various outfall design concepts. This use of such standards and guidelines is, in one sense, arbitrary in that all of the other factors mentioned above are also taken into account in the actual evaluation of a proposed once through cooling system. However, it does allow an assessment of the feasibility, in general terms, of using once through cooling for various combinations of power plant generating capacities, receiving water types, and outfall design concepts.

Four generic classes of receiving water bodies (rivers, lakes, estuaries, and open coastal waters) and four typical large power plants (500 MW fossil, 500 MW nuclear, 1000 MW fossil, and 1000 MW nuclear) were used to form a framework for the assessment. Various outfall designs ranging from conventional, low velocity, shoreline, surface discharges to long, high velocity, offshore, submerged multiport diffusers were considered. Many of the results obtained in this study are subject to numerous qualifications and limitations, however, a few general conclusions can be drawn.

The initial dilution attained by a shoreline surface discharge, and therefore the size of the mixing zone, is strongly influenced by the physical characteristics of the ambient receiving water. In the case of rivers, the

minimum river flow rate for which typical thermal standards can be met. For example, a 500 MW fossil plant would require a river flow rate of about $180 \text{ m}^3/\text{s}$ and a 1000 MW nuclear plant would require $520 \text{ m}^3/\text{s}$. Only the major river systems in the U.S. have flow rates which are consistently this large. In large lake applications, surface discharges might be acceptable for power plants with capacities $\leq 500 \text{ MW}$, if a mixing zone with a surface area of $2.9 \times 10^5 \text{ m}^2$ (equivalent to a circle with a 1000 ft radius) or larger were allowed. Larger power plants with surface discharges would require mixing zones that would exceed most standards and guidelines. The large dilution typically required at estuarine and marine sites essentially precludes the use of shoreline surface discharges for large power plants.

The initial dilution attained by submerged outfalls, especially high-velocity, multiport diffusers, is governed primarily by the characteristics of the discharge rather than the characteristics of the receiving water. Therefore, water depth, rather than the presence of natural current, is generally the most important characteristic of the receiving water body. However, in riverine and certain estuarine cases, the total natural flow past the diffuser site is often the factor which limits dilution. It appears to be possible to design a multiport diffuser with a reasonable discharge velocity which will result in full mixing of the effluent with the total river flow. This places an extreme lower limit on the flow rate of the river needed to support once through cooling. However, the restriction that a zone of passage equivalent to $3/4$ of the cross-sectional area of the river be maintained, requires larger river flow rates. For example, a 500 MW fossil plant would probably require a river flow rate of $100\text{--}150 \text{ m}^3/\text{s}$ and a 1000 MW nuclear plant would require $300\text{--}400 \text{ m}^3/\text{s}$. Multiport diffusers appear to be very promising for use in large lakes. Even in fairly shallow water ($\approx 5 \text{ m}$) a diffuser of reasonable length ($<350 \text{ m}$) and discharge velocity ($>2 \text{ m/s}$) should be able to attain the dilution required for a power plant as large as 1000 MW to meet typical thermal standards. Multiport diffusers for use at estuarine and marine open coastal sites must be designed to produce large dilutions (≈ 12). In estuaries, complex density and current structures and other complicating factors make a general analysis of submerged multiport diffusers impossible. The need for large dilutions, the presence of bi-directional tidal currents, limited flushing and the need to maintain a zone of passage requires that much care be taken in selecting the type of diffuser to be used at a specific site. Open coastal sites are less restrictive in that only the initial dilution in the vicinity of the outfall is critical. Coastal currents will often be present to carry away the diluted waste heat and the lack of a far boundary and the offshore location of the outfall precludes the need of a zone of passage. In general, diffusers will have to be at least 3-5 times larger than those needed for lake sites where comparable water depths are available.

It has been shown in this study that once through cooling water systems for single plants or generating units may be designed to operate, in some circumstances, within water temperature limitations. However, the cumulative effects of a number of power plants on the same receiving water body

through cooling, obviously, and the potential disruption of relative effects of impingement and entrainment, must be considered. Estimates of coastal migration patterns, and the like must be considered. Estimates of physical thermal impacts of multiple plants can be made and should be carried out at a first step in water-body-wide assessments. Determination of the number, distribution, and capacity of potential waste-heat disposal sites for power generation with once through cooling for the upper Mississippi and Missouri Rivers using a numerical model by Paily et al.³⁵ represents a useful prototype for such studies.

ACKNOWLEDGMENT

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and

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INTRODUCTION

This paper deals with the environmental benefits of integrated community energy systems. It discusses specific cases and demonstrates how use of appropriately sized community energy systems that combine heat and power generation both conserve scarce fuels and reduce air pollution emissions. The discussion is based on work undertaken on behalf of the Department of Energy's Community Systems Program.

The goal of the Community Systems Program is to help communities develop and put into practice effective energy conservation programs. To do this, the program develops and applies approaches to community energy conservation that:

- combine use of the energy resources available within a community, reducing reliance on external and scarce fuels;
- increase the use of fuel-efficient energy systems in supplying utility services;
- substitute energy systems that use non-scarce fuels for those that consume oil and natural gas; and
- reduce the end-use demand for energy through planning and development practices.

Applied separately, these approaches can save significant amounts of energy; however, maximum conservation can be achieved in a particular community through a carefully-planned combination of them (see Fig. 1). Therefore, the Community Systems Program is developing a comprehensive approach to energy management that coordinates community design and development with the capacity expansion of utility supply networks.

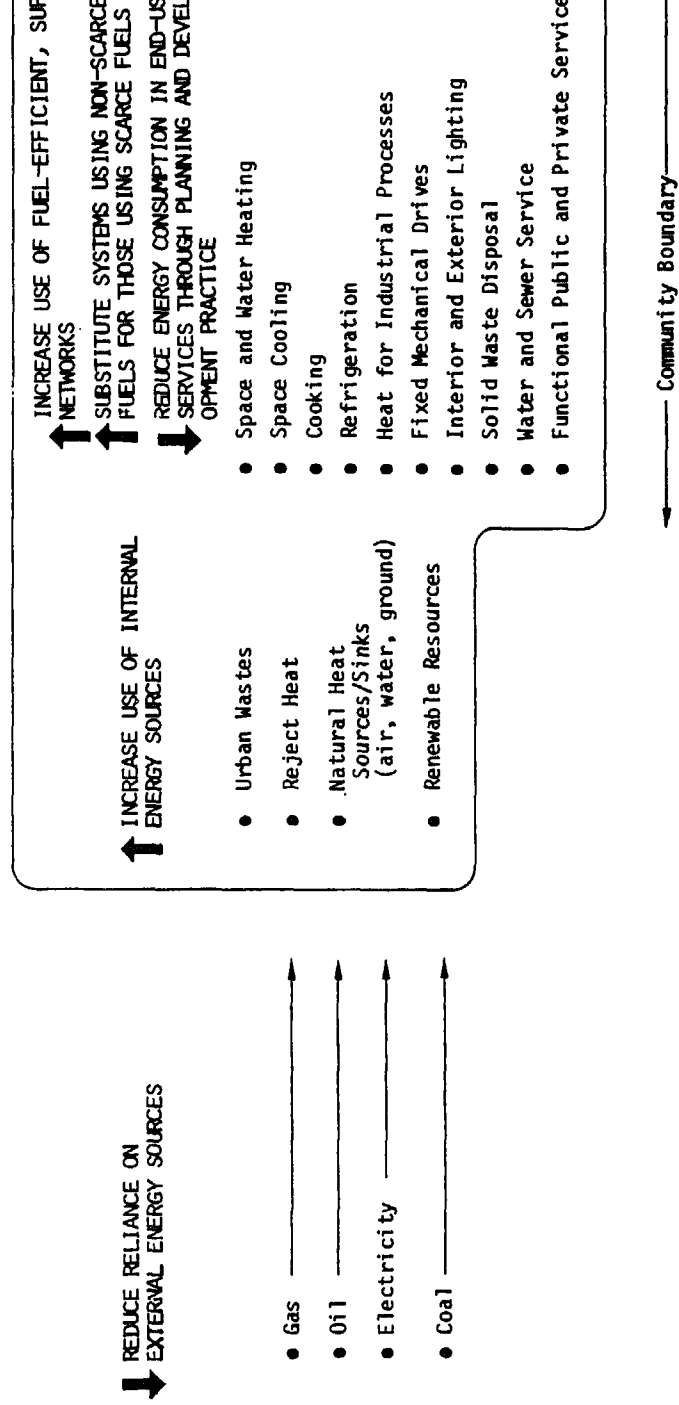


Fig. 1. Community Energy Supply and Demand

tem is a concept for system operation, as a result, the possible configurations of generating equipment, distribution techniques, and end-use conversion appliances that can be employed in developing such a system.

BACKGROUND

The grid-connected community energy system concept is related to, but different from, the total energy system concept. The typical total energy system operates in response to electric power demand with the system's thermal output considered a byproduct that can be utilized for space conditioning or other services. During periods of imbalance between electric power demand and thermal demand, the overall fuel conversion efficiency of a total energy system is greatly reduced.

The grid-connected community energy system overcomes the inefficiencies caused by imbalances between thermal energy demand and electric power demand by being connected to the local electrical utility grid. The system is operated primarily to meet community thermal demands; any shortfalls or surpluses in electrical energy requirements can be accommodated by exporting to or importing from the local utility grid. Since the grid connected system operates only in response to thermal demand, there is, by definition, no usable heat energy wasted.

The Community Systems Branch of the Department of Energy is now engaged in a program to demonstrate the feasibility of the grid-connected community energy system. Work is being carried out at four sites: The University of Minnesota's Minneapolis Campus; Clark University in Worcester, Massachusetts; Trenton, New Jersey; and New Orleans, Louisiana. One of the important objectives in this demonstration program is to show that grid-connected systems can supply community energy needs in an environmentally acceptable manner. The following discussion illustrates that the systems proposed for the University of Minnesota and Clark University not only conserve energy but offer environmental benefits to their communities in the form of reduced emissions.

DEMONSTRATION PROGRAM RESULTS

The University of Minnesota

The University currently operates a campus-wide district heating system supplied from a plant originally designed to burn oil or natural gas to produce steam. In recent years, the University has been slowly converting to coal. As a result of the Demonstration Program, the University plans to speed its fuel conversion program and to burn low-sulphur western coal.

ing of eight million barrels of oil a year. In addition, despite converting to coal, installation of the grid-connected system will reduce emissions in Minneapolis, currently a non-attainment area for particulates and SO₂ emissions.

Table 1 sets forth the current emissions for the University of Minnesota steam plant and for the steam plants of St. Mary's and Fairview Hospitals and Augsburg College. Table 2 sets forth the projected emissions from the coal burning grid-connected community energy system. As can be seen, total SO₂ emissions are expected to fall by some 250 tons per year. Particulate emissions, although increasing somewhat, fall well within the Minnesota Pollution Control Agency's guidelines for new or modified stationary emission sources. These results, it should be noted, do not take account of reduced emissions from electric generating facilities owned by the local utility, Northern States Power Co. Clearly, the University of Minnesota project will provide a net reduction in air pollution emissions to the Minneapolis area.

Table 1. Present Air Pollution Emissions from University of Minnesota Heating System and from the Heating Systems of St. Mary's Hospital, Fairview Hospital, and Augsburg College (Tons/Yr)

Type	3 Institutions	Univ. of Minn.	Total
Particulates	19.28	66.40	85.72
SO ₂	408.83	5730.05	5979.31

Source: See Table 2.

Table 2. Projected Emissions from Proposed Grid-Connected Community Energy System (Tons/Yr)

Type	Emission Rate
Particulates	138.02
SO ₂	5730.05

Source: Grid Connected Community Energy System, Phase II, Final Stage 2 Report, University of Minnesota, prepared for the U.S. Department of Energy under Contract No. EC-77-C-02-4210.

energy costs increased from \$51,000 to \$101,000.

Clark proposes to replace its three existing oil-fired boilers with a 1.4 MWe ebulliently cooled diesel-generator unit featuring waste heat recovery to supply low pressure steam; a new waste heat boiler supplying high pressure (125 psi) steam will be installed to serve the majority of existing buildings. The size diesel selected will supply only about one-third of the University's thermal demands but virtually all its electric energy needs.

As a result, the University expects to operate the diesel at close to full load for approximately 8,000 hours per year. The University has negotiated an innovative arrangement for grid-connection with the Massachusetts Electric Company. Electrical output from the diesel generator will be connected to the load side (the utility side) of the meter. This results in all University electrical requirements being satisfied before any energy is fed into the Massachusetts Electric grid, and reduces demand on the utility for billing purposes. Thus, the University realizes dollar savings by supplying its own electrical requirements and by selling excess electrical energy to the local grid. This mode of operation will reduce University annual oil consumption by 21%, or 309,000 gallons.

At present, the Worcester area is a non-attainment area for particulates. The proposed grid-connected system will reduce particulate emissions from their current levels, have a negligible effect on other pollutants except NO_x , which will increase. Table 3 compares emission data for the present system with emissions for the proposed grid-connected system. As can be seen, Clark's proposed community energy system will, on balance, make a significant contribution to reducing air pollution emissions in the Worcester, Massachusetts, area.

Table 3. Air Pollution Emissions from Present Clark University Heating System and from Proposed Grid-Connected Community Energy System (Tons/Yr)

Type	Present System	Proposed System
Particulates	4.7	1.9
SO_2	114.3	90.1
NO_x	79.5	178.3

Source: Grid Connected Integrated Community Energy System, Draft Final Report, Vol. II, Clark University, Worcester, Massachusetts, prepared for the U.S. Department of Energy under Contract No. EC-77-C-02-4211.A001.

case, reducing fuel requirements resulted in significant reductions in those emissions considered critical in each region. Integrated community energy systems have the potential for replacing many point emissions sources with one source and substantially reducing community fuel requirements. Although further research is necessary, the integrated community energy system has the potential for becoming an important tool in enhancing air quality in the nation's cities.

1.0 INTRODUCTION

Dry cooling of thermal power plants has been the subject of many economic studies and several research programs funded by Department of Energy (DOE) and other organizations such as the Environmental Protection Agency (EPA) and Electric Power Research Institute (EPRI). The studies have been directed at comparing dry cooling with alternative heat rejection systems: once-through, evaporation, and other types that heat up or consume water, as well as with various types of dry and combination systems. The research programs have focused on ways to reduce the cost of dry cooling, since this method of heat rejection generally projects out to be more expensive than other conventional ways of cooling power plants.

The interest stems from the growing realization that the use of fresh inland water to provide a heat sink for the thermal generation of power cannot continue to increase indefinitely. Excluding for the moment the rejection of heat to ocean bodies, one concludes (from comparisons of project power needs with the available fresh water runoff in various sections of the country) that the consumptive use of water for evaporative cooling will have to be supplemented by growing amounts of dry cooling in the next ten to twenty years. Except in special situations, it seems likely that this supplementing will occur through the use of combination wet and dry systems, because using a small amount of cooling water gives a disproportionate benefit of dry cooling systems. Thus, whenever the term dry cooling is used in this paper, the use of dry/wet cooling is also implied.

The Dry Cooling Enhancement Program (DCE) at the Pacific Northwest Laboratory (PNL) has been focused on the development of technology and the initial planning (including the investigation of justification) for a large-scale test, the advanced concept test (ACT). The overall program objective has been to develop technology to relieve the water shortage anticipated in many of the sections of the country through encouraging the use of lower cost dry cooling in power plants. Only through the transfer of this technology to the commercial market will this effort have any impact on the national problem of growing competition for existing water supplies.

The DCE activities can be categorized into five areas which go together to make up this thrust:

- studying the anticipated need for dry cooling and the payoff from a successful demonstration of an improved system
- evaluating existing technology to identify the areas in which improvement could be made

leading candidate for large scale testing

- developing a consensus among various elements of the utility industry as to the wisdom of proceeding with the ACT project and structuring a funding base to carry out the project.

The DCE program has been coordinated with an EPRI program at Union Carbide Corporation/Linde Division, which has also been directed toward evaluating and testing a particular advanced dry cooling concept—the use of ammonia as a heat transport media between the generating plant and the dry cooling tower. This paper emphasizes the DOE program but the significance and role of this EPRI program must be given recognition from the start, particularly since some of the key development work in support of the large-scale test has been, and continues to be, done by the EPRI program at UCC/Linde.

Initially DOE was to have had the lead role in the large-scale test and the overall funding was to have been about 50-50 between the private and governmental sectors; however, governmental support for the program has not developed to that degree. At the present time, the Environmental Control Technology and Advanced Concept Assessment groups in DOE plan to support the test in a limited way. The EPA has also indicated their interest in the project. Nevertheless, the EPRI has decided that the need for this technology within the utility industry is sufficiently pressing to justify their going ahead with the design and construction phases of the project on the basis of this limited assured Federal support.

The DOE role in the present fiscal year is one of assessment. Now that a selection of an advanced concept for demonstration has been made, identifying further improvements that can be made, based on that technology, and answering questions of interfacing with the environment, will be the objective of the continuing DOE programs.

This paper summarizes the accomplishments of the DCE program by presenting them in the context of steps toward the establishment of the ACT project. Thus the paper addresses:

- the purpose of a federally funded program for seeking lower cost dry/wet cooling systems
- the prospects for achieving lower cost systems
- the payoff anticipated from a successful demonstration
- the procedure underway for the ACT project.

two factors in the justification of an advanced dry cooling system have been investigated extensively--the projected need for dry cooling in the next 15 to 20 years and a representative survey of industry attitudes toward a demonstration project.

2.1 PROJECTED NEED FOR DRY COOLING

It is very difficult to predict the extent to which dry cooling will be used in the next 15 to 20 years. Current costs for dry cooling have encouraged power companies to generally conclude that, if water can be obtained by any means, evaporative cooling should be used instead of dry cooling. The lower cost and higher operating efficiency of wet cooling, as well as familiarity with this technology, support this conclusion. Thus the local availability of water for cooling, considering both physical and legal constraints, as compared with the projected need for power, will determine the incentives for dry cooling.

The comparison between the physical availability of water and projected need for new generating facilities was reported in a recent study by Peterson and Sonnichsen.⁽¹⁾ However, the study did not consider possible regulatory action which could restrict the use of water for cooling. Instead, 10 percent of the 10-year monthly low flow was assumed available for evaporative cooling. The study concludes that, based on its assumptions, even where water for cooling is in short supply, there appear to be economic alternatives to dry cooling up to approximately 1990, except in isolated cases (notably at two mine-mouth locations at Wyodak, Wyoming and Farmington, New Mexico). Between 1990 and 2000 the imbalance between available water and projected power generation becomes acute in several regions, as shown in Figure 1. Based on the 1972 power projections presented in WASH-1139⁽²⁾ the study concludes the nation will need from 20 to 39 GWe of electrical generation with dry/wet or dry cooling by the year 2000.

These power projections are believed to be somewhat high but the Sonnichsen study is based on an arbitrary availability criteria that may not be permitted by the respective state agencies responsible for water allocation. As part of the DCE program Hendrickson⁽³⁾ made a study of the issues affecting the demand for dry cooling. (The study was made in the Spring of 1977 and updated in the Fall of this year.) He concluded the requirement could be as high as 45 GWe or as low as 10 GWe. The great uncertainty stems from the uncertainty of legal actions that may be taken in a number of states to limit the transfer of water from agricultural to industrial use. There are some indications that such restrictions are increasing, reflecting concerns that established agricultural and community infrastructures will be damaged by such water transfers.

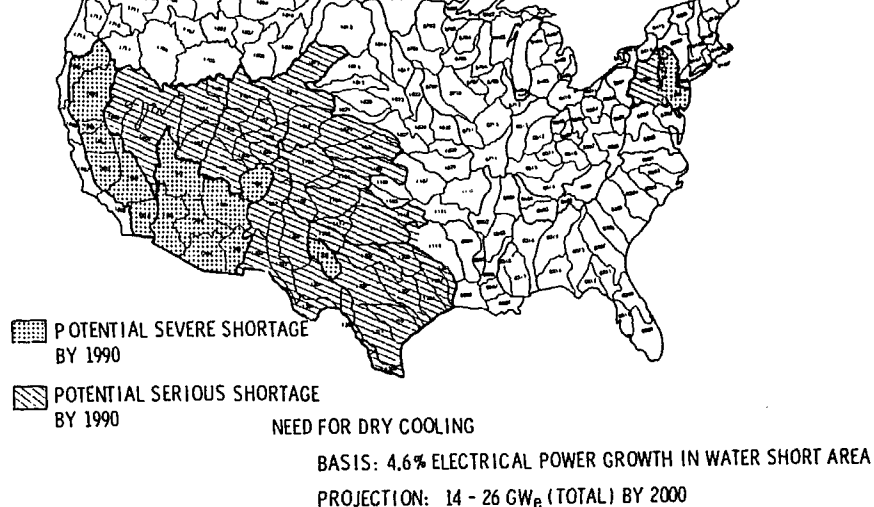


FIGURE 1. Areas of Potential Water Shortage for Power Plant Cooling

2.2 INDUSTRY ATTITUDES TOWARD DEMONSTRATION

Commercialization of the advanced technology is the ultimate objective of the demonstration. This is more likely to occur if there is interest in the performance of the demonstration and if there is a consensus among the various segments of the utility industry that need for demonstrating an advanced system exists, that the proposed advanced system warrants demonstration, and that this system will be accepted by the industry if the demonstration is successful. PNL has attempted to ascertain whether such a consensus exists or can be developed. To do this, copies of PNL reports summarizing the comparative economic studies of several all-dry and dry/wet systems and a report of the conceptual design of the proposed demonstration facility were sent to a group of companies and organizations involved in power plant heat rejection technology. Included were nine utilities (primarily in the Southwest), five manufacturers, three architect/engineering companies and two government agencies.

Utility responses generally reflected considerable interest in the demonstration with an emphasis on the need for reliability. Some reservations about specific aspects of the advanced concept proposed for demonstration were expressed, but the great majority felt the concept showed considerable promise and should be further investigated, and that the demonstration would be very beneficial.

The utilities contacted seemed to agree that the cost of present dry/wet cooling systems is so high that use of dry/wet cooling will occur only in isolated situations unless significantly lower cost systems can be developed.

expend a great amount of private capital to develop and demonstrate radically new approaches. Yet without large-scale demonstration, utilities will not adopt new technology in cooling systems. Hence, the need is felt for government and utility assistance to spur development.

Two manufacturers provided comments reflecting skepticism that marked improvements on their engineering designs were being offered. One stated that insufficient backup data for the cost estimates were provided to conclude there was sufficient incentive to proceed with the proposed system. This manufacturer felt, and it seems fair to say, that "...the support for the program must come from the electric generating industry. Without a sincere desire on the part of the electric generating industry to fund and demonstrate such a project [we] can see no justification for spending Federal funds to provide segments of private industry a development site and monies for private development."

The other company felt the demonstration of the proposed concept was a good idea, and that much of the technology involved was state-of-the-art, although not in the power station heat rejection field. However, they were skeptical about the proposed method of accomplishing augmented cooling, favoring instead the separate dry and wet towers approach which allows consideration of their current dry tower designs. Still they felt the demonstration is worthwhile.

A third company verbally expressed interest in the demonstration but did not comment in writing on the reports. No replies were received from two companies.

The two A/E firms provided verbal comments following brief reviews. Both felt the proposed dry cooling concept should be demonstrated. It is significant that all of the seven A/E firms considered to be leading candidates for performing the design and construction project management of the ACT project submitted proposals for this work.

Both government agencies contacted were supportive of a demonstration of the proposed advanced concept and indicated a willingness to discuss partial support of the project.

reduction. Dry cooling has been technically feasible on a large scale for nearly two decades, as witnessed by the successful operation of the 120-MWe installation at Rugeley, England⁽⁴⁾ since 1961. However, the cost has remained prohibitively high except for a few special mine-mouth situations in unusually water-short regions.

To better establish the basis for the present use of dry cooling, two surveys of this technology were made by the DCE program. One by DeSteele and Simhan⁽⁵⁾ considered the European experiences only; the other by Johnson, Pratt and Zima⁽⁶⁾ summarized the experience in this country, particularly in the chemical processing industry and as large interstage coolers for gas pipeline pumping stations. The former sought to establish the complete spectrum of operating and maintenance experience as well as the motivating influence behind the selection of dry cooling, while the latter emphasized the materials and corrosion performance. A later report by Johnson, Begaj, Martini and May⁽⁷⁾ examined the metallographic aspects of aluminum alloy performance under dry cooling conditions.

The real cost of dry cooling is not well established. The ancillary costs for capacity and energy replacement are uncertain and highly dependent on the assumptions used in the evaluation. A DCE study by Fryer⁽⁸⁾ of the various methods used in the many studies made to date served to bring these uncertainties into focus and resulted in a recommendation that more meaningful projections could be made by using the methodology of marginal power pricing considering the utility as a whole, rather than the present approach of considering the dry-cooled plant as an isolated generating unit. This is important because these penalties for capacity and energy replacement are sufficiently large to dominate the system design optimization and through it, the size and cost of the dry cooling tower.

A large number of system design studies and analyses have been performed and significant differences exist among them. Table 1 provides a very approximate distribution of subsystem costs for dry cooling systems. Results of individual analyses vary by as much as ± 10 percent from some of these percentages. Nevertheless, the table does point out that the entire system, not just the heat exchanger, must be considered if significant cost reductions are going to be achieved. Probably "revolutionary" rather than evolutionary changes in dry cooling systems will be needed to accomplish significant reductions.

To gain a better first-hand understanding of cost and operational aspects of state-of-the-art dry/wet cooling as a point of departure for developing improved systems PNL (i.e., DOE) has cooperated with a consortium of utilities, California state agencies and the EPRI in a testing of a dry/wet tower (approximately 10 MWe equivalent) constructed by the Ecodyne Company for Southern California Edison at San Bernadino. In addition to contributing materially to the program, the DCE program provided the initial test plan and

Subsystem	
Heat Exchanger	30
Structure	15
Fan System	20
Piping and Pumps	20
Condenser	15
Total ~\$55/kWe (1000 MWe-1976)	100

the analysis of uncertainty of the instrumentation and measurements. These tests are in progress but the experience gained to date is being factored into the design and testing program for the Advanced Concept Test discussed in Section 5.0.

3.1 NEW SURFACES FOR CONVENTIONAL DRY AND DRY/WET COOLING PROCESSES

Dry cooling R&D may be categorized as being directed primarily at the development of new heat transfer surfaces or at the development of new processes. Table 2 summarizes the work on new surfaces that have been considered by the DCE program, showing the organization doing the work and status of its efforts.

TABLE 2. New Surfaces for Conventional Dry and Dry/Wet Cooling Processes

Surface	Laboratory Studies	Conceptual Design and Cost Estimate	Status		Organization
			Demonstration Planned		
Plastic Tube	X	X	X		Italmimpianti PNL
Plastic Sheets	X				Battelle-Geneva
Chipped Fin	X	X			Curtiss-Wright Linde
Expanded Metal	X				Linde Energy Research Corp.
Fluidized Beds	X	X			MIT PNL Idaho Nuclear
Packed Bed	X				MIT
Modified Tower Packing for Wet/Dry Cooling	X				MIT

proposed based on this approach: a plastic tube dry tower, suggested by Roma and being developed by Italimpianti⁽⁹⁾ (Figure 2); and a plastic sheet design developed by Battelle-Geneva.⁽¹⁰⁾ The Italimpianti design has received considerable publicity in the United States as well as in Europe and appears to offer attractive cost savings. However, since much of the information is held proprietary and the labor/materials cost tradeoffs differ considerably between Italy and the U.S., direct comparisons are difficult to make. In spite of these uncertainties, the approach was included in PNL cost studies for the 1000-MW dry cooled plant at Wyodak, Wyoming⁽¹¹⁾ and for a 500-MW dry/wet system at Farmington, New Mexico.⁽¹²⁾ The costs were comparable to the optimized conventional technology for the all-dry case and resulted in an 8 percent additional savings in the dry/wet case.

A cooling system under development at Battelle-Geneva⁽¹⁰⁾ incorporates a novel cross-flow heat exchanger in the dry section. The water flows as a falling film in alternate passages created by a series of parallel, thin (0.2 mm) plastic sheets. No studies of this approach have been conducted by PNL.

Novel methods of producing extended metal surfaces and integrating them into heat exchanger modules show potential for substantial cost reduction. A machining process for producing integral fins on a tube (Figure 3) has been studied for potential dry cooling application by

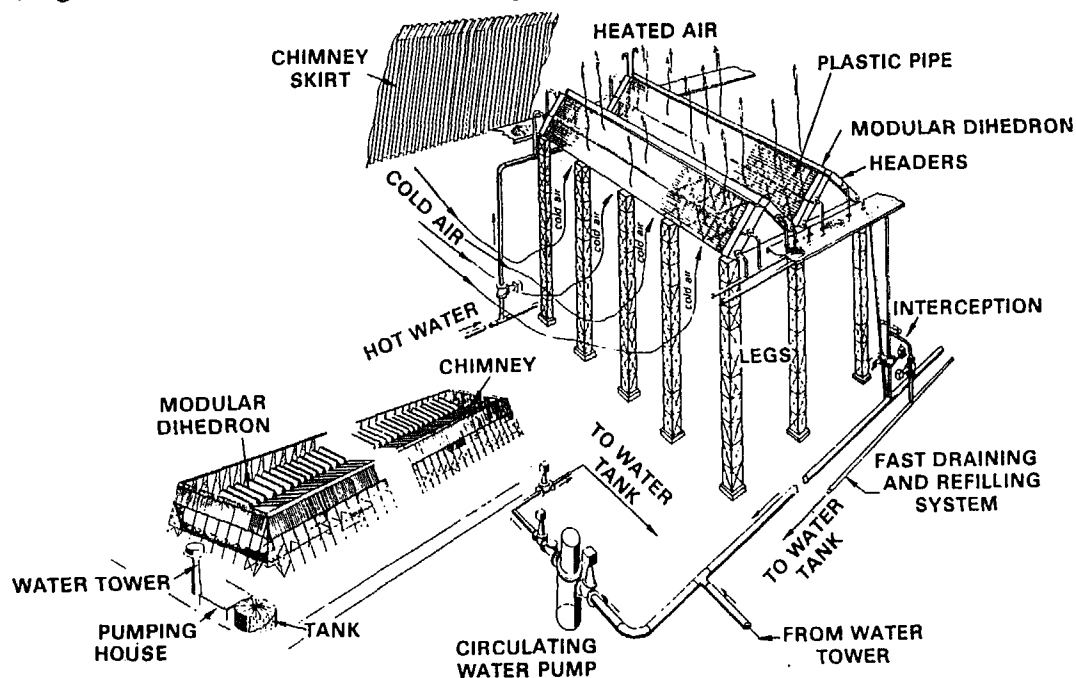


FIGURE 2. Conceptual Sketch of Dry Cooling Tower Using Plastic Heat Exchangers⁽⁹⁾

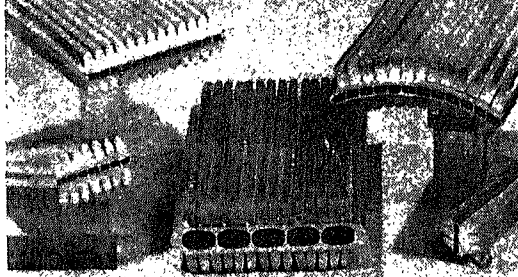


FIGURE 3. Curtiss-Wright Chipped
Fin Surfaces

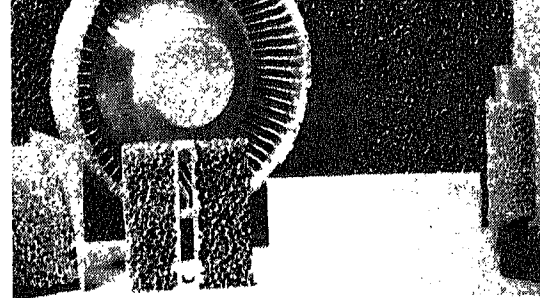


FIGURE 4. Metal Matrix-Energy
Research Corporation

Curtiss-Wright Corporation under ERDA sponsorship⁽¹³⁾ and by EPRI.⁽¹⁴⁾ The surface has seen successful commercial application in automotive air conditioning and appears to offer substantial cost savings due to ease of module fabrication and assembly. This surface has shown cost advantages over conventional fin tube designs in an advanced dry cooling tower concept using a phase-change fluid in the condenser transfer loop, as discussed in a later section. On this basis it has been tentatively selected as one of the surfaces to be tested in the ACT facility.

Another approach to extended surface heat exchanger design is the use of a foam metal matrix (Figure 4) as proposed by Energy Research Corporation. The application of this surface to dry tower design has been studied as part of the EPRI/Union Carbide development work.⁽¹⁴⁾ Excellent heat transfer versus pressure drop characteristics are obtained. This is consistent with the analytical work of Moore⁽¹⁵⁾ who concludes that the use of small hydraulic diameter surfaces in a shallow, high-frontal area configuration leads to an optimal arrangement. The costs of module fabrication and the potential operating problem of in-service fouling are to be the subject of further study to properly evaluate the surface.

An alternative approach to the use of lower-cost heat exchangers is the augmentation of the limiting air-side heat transfer rate with the intent that reduced surface requirements will offset any increase in the per unit area costs. Fluidized beds have been studied by several investigators at Dynatech,⁽¹⁶⁾ MIT,⁽¹⁷⁾ and Allied Chemical⁽¹⁸⁾ because of the very high heat transfer rates attainable. In all cases the excessive fan power required to fluidize the bed was shown to outweigh the benefits from the increased heat transfer. The difficult engineering problems of designing the tower to contain the fluidized bed and the operating problems of agglomeration and particle loss were never addressed in depth. In a similar vein, the packed bed design was proposed by Andeen et al.⁽¹⁹⁾

erent process are summarized in Table 3. In these, the principal emphasis is not on the development of a more cost effective extended surface but rather on new ways of transferring the heat from the power plant to the air. A different fluid used to transport the heat, a completely different approach to effecting the heat transfer, or a different method of obtaining augmented cooling during hot weather are the characteristics of these approaches.

TABLE 3. New Dry/Wet Cooling Processes

Process	Laboratory Studies	Conceptual Design and Cost Estimate	Status	
			Demonstration Planned	Organization
NH ₃ as Heat Transfer Fluid	X	X	X	Franklin Institute PNL Linde
NH ₃ Heat Pipes	X	X	X	McDonnell Douglas Foster Wheeler
Deluge Cooling	X	X	X	PNL HÖTERV (Hungary)
Rotating Discs	X			MIT Air Preheater Corp.
Capacitive Ponds	X	X		PNL MIT Auburn University

The use of a phase-change fluid in the condenser to cooling tower heat transport loop has been studied in several variations by the Franklin Institute, (20) PNL, (11) and Union Carbide. (14) Three advantages leading to reduced system cost are: 1) reduced pumping power in the transport loop, 2) elimination of the transport loop range as a temperature increment between the ambient dry bulb and condensing temperatures, and 3) the ability to use high performance surfaces on the ammonia side of the steam condenser/ammonia reboiler to reduce the condenser terminal temperature difference. This system, which has been selected for demonstration, is described more fully in Section 3.3.

Modular arrangements of heat pipes filled with NH₃ and protruding from extensions of exhaust steam ducts leading out from the power plants are being developed jointly by Foster Wheeler and McDonnell Douglas. The rejection of heat equivalent to that from a 1.5-MWe power plant has been under demonstration at a small power plant in Wyodak, Wyoming since early in 1978. No results have been made public as yet.

a thin film of water so that evaporative cooling and sensible heat transfer occur simultaneously, appears to be a relatively simple and inexpensive way of achieving augmented cooling (i.e., dry/wet cooling). However, several uncertainties must first be overcome in performance prediction and proper design of the extended surface to permit good dry performance, together with proper coverage to avoid scaling and corrosion. The concept has been developed by HÖTERV Institute of Hungary and is being demonstrated at a 60-MWe district heating plant near Moscow in the USSR. Intensive study of the approach is being conducted by PNL.⁽¹²⁾ Deluge cooling has tentatively been selected for demonstration and is further discussed in Section 3.3.

A novel configuration, developed and tested at MIT, consists of rotating discs, semisubmerged in a water bath covered with oil film (Figure 5). The discs are alternately heated in the water, then exposed to an air flow for cooling. The oil film inhibits wetting of the discs while permitting unimpeded sensible heat transfer, resulting in a "dry" heat exchanger. Promising laboratory results have been reported.⁽²¹⁾ Engineering development work to resolve the formidable problems of mechanical design, potential fouling, and emulsification of the oil film is underway at Air Preheater Corporation, under license to MIT.

The use of water as a thermal storage mechanism for the smoothing of diurnal peaks in dry cooling capacity has been studied at Auburn University⁽²²⁾ and MIT.⁽²³⁾ Excess tower capacity at night is stored as cooled water for supplemental cooling use during the peak-load high-temperature afternoon hours.

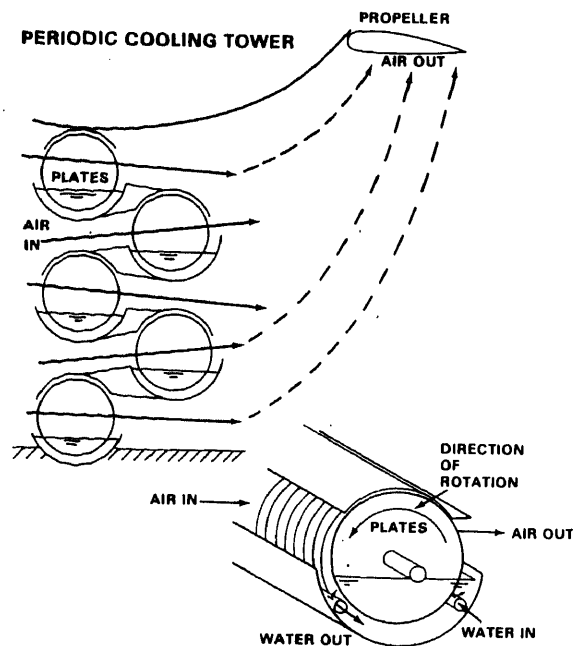


FIGURE 5. Rotating Disc Cooling Concept - MIT

While the approach primarily appears technically feasible and economically attractive from initial studies, more detailed analyses⁽²⁴⁾ as part of the DCE Program have led us to conclude it is of limited value - only in locations with very high peak temperatures. To some extent the arbitrary ground rules of the presently accepted methodology for evaluating dry cooling may be the cause of the relatively discouraging assessment. Use of more involved (and more realistic) marginal pricing analysis for a particular utility may show the concept has more merit than our present evaluation.

To provide a basis for a detailed evaluation of the cost-effectiveness of those new surfaces and new processes which were initially judged to be most promising and to assess the incentives for further development of one or more of them, the DCE Program has carried on two types of studies. One approach has been to develop computer codes which provide the projected costs of optimized designs of several all-dry⁽²⁵⁾ and dry/wet⁽²⁶⁾ concepts. An exhaustive survey of the world literature on heat transfer and pressure drop characteristics of dry tower surfaces was made to provide impact into the optimization studies.⁽²⁷⁾ The second approach has been to develop conceptual designs and engineering cost estimates of a number of dry/wet systems for a particular set of site conditions and power plant design parameters. A nominal 500 MWe coal-fired plant located at Farmington, New Mexico, with a heat rejection requirement of 2.5×10^9 Btu/hr was the basis selected. Two such studies using this second approach have been completed. In one, five different types of dry/wet systems were compared⁽¹²⁾ and in the second four other approaches were evaluated.⁽²⁸⁾ Two approaches representing the present state-of-the-art were included to provide the indication of the prospective cost effectiveness of the new approaches.

Using the design optimization code for all-dry systems, conventional finned-tube heat exchangers of two types, using circulating water in an indirect system, were compared with a proposed system containing plastic-tube heat exchangers (and also using circulating water) and with an ammonia system using conventional finned tubes. The results⁽¹¹⁾ are shown in Figure 6 and summarized in Table 4.

TABLE 4. Comparison of Incremental Cost Savings
for Advanced All-Dry Cooling Systems

<u>Cooling System</u>	<u>Percent Reduction in Incremental Power Production Cost</u>	<u>Percent Reduction in Total Power Production Cost</u>
State-of-the-Art Conventional	0	0
State-of-the-Art Inexpensive Tubes	11.1	1.5
Plastic	22.2	2.8
NH ₃	34.2	4.1

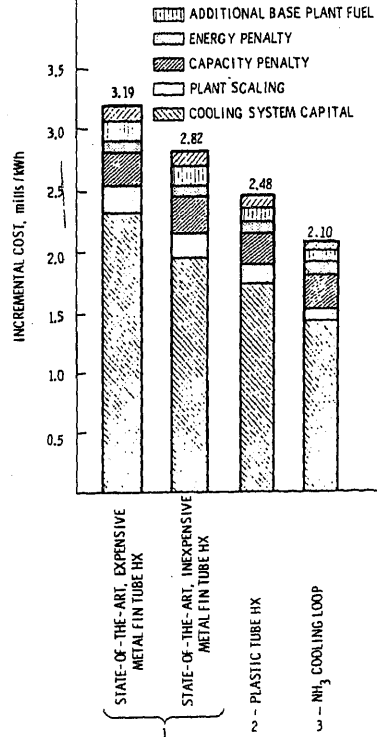
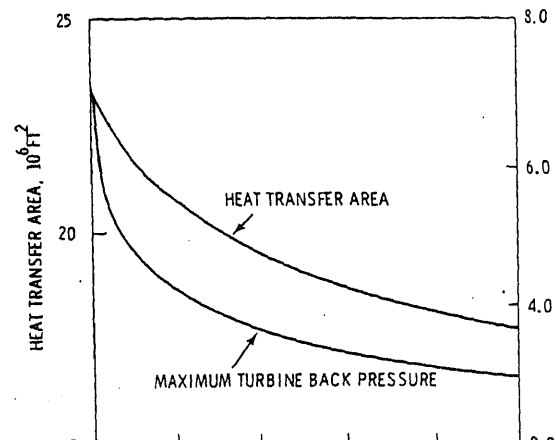
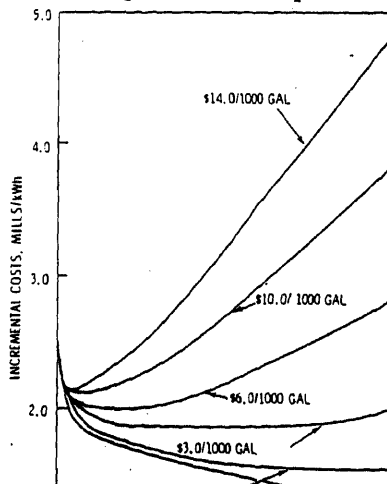


FIGURE 6. Comparison of Incremental Power Costs Using 3 Different All-Dry Concepts.

Similar design optimization studies of dry/wet systems using the delug approach⁽²⁸⁾ have shown the savings resulting from the use of enhanced cooling using evaporative cooling (Figure 7). One marked incentive to the use of dry/wet cooling is the avoidance of the need to consider the high back pressure turbine. As seen in Figure 8, the maximum back pressure stipulated in an optimum dry/wet system located at Wyodak, Wyoming, is less than the maximum allowed with a conventional turbine at all but very low water availability (less than 33 percent required for total evaporative cooling).



tially to compare five alternative dry/wet concepts, one of which incorporated the use of ammonia.⁽¹²⁾ The five were selected for the following reasons:

- Integrated dry/wet tower - The evaluated configuration was essentially the same as that planned for the San Juan Unit 3 and consequently provided a base case reference to state-of-the-art technology in a dry/wet cooling system (Figure 9).

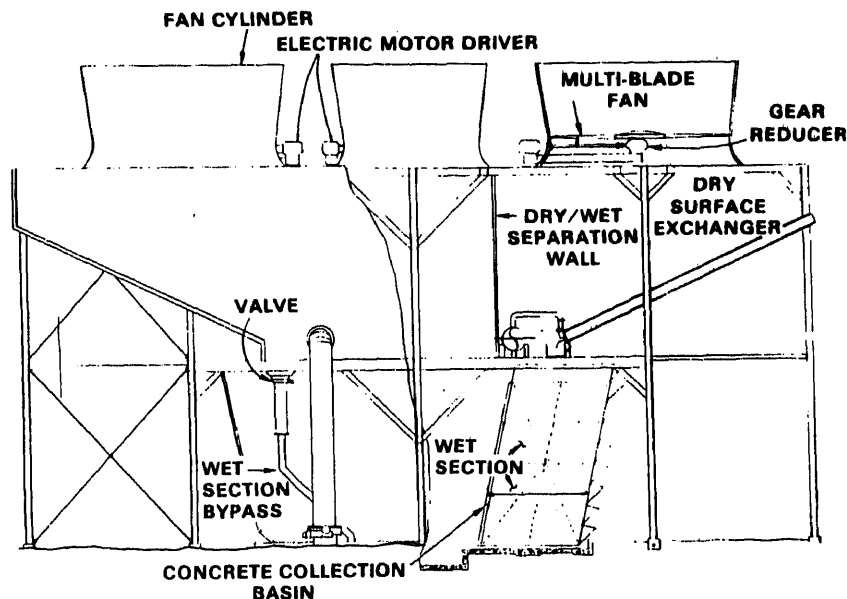


FIGURE 9. Integrated Dry/Wet Cooling Tower

- Separate dry and wet towers - A recent study of the use of separate dry and wet towers⁽²⁹⁾ has suggested several important operational and cost advantages. This concept evaluation provides a comparison to the cost advantages relative to this application of existing technology.
- Metal fin-tube with deluge augmentation - The deluge cooling concept has been under study in eastern Europe and is believed to have some important advantages. (However, subsequent studies indicated that the configuration selected in the conceptual design of this and the ammonia system could be improved upon significantly as was done in the second study.⁽²⁸⁾)
- Plastic heat exchanger^(a) with deluge augmentation - The plastic system is well-suited for this concept

(a) A natural-draft plastic system is under active investigation by Italimpianti in Italy, but differences between that system and the mechanical draft system studied here are sufficiently great that it is difficult to make a direct comparison of the Italimpianti system with the mechanical draft system.

because the tubes are not subject to corrosion, have low susceptibility to fouling, and low likelihood of freezing damage. The smooth tubes make the tradeoffs of design conditions between dry and deluge operation less difficult to reconcile.

- The ammonia heat transport system with metal fin-tube heat exchanger and deluge augmentation - The advantages of using ammonia in an all-dry system (smaller pipelines for the fluid, lower pumping requirements, no freezing problems and a higher heat transfer temperature difference in the cooling tower) would also apply to augmenting an all-dry ammonia system with a deluged system.

In the second study⁽²⁸⁾ four dry/wet systems using ammonia were compared with each other and with the base-line configuration - the integrated dry/wet system using circulating water for condenser cooling. The four systems were:

- the HÖTERV plate fin with deluge augmented cooling (vertical round towers)
- the HÖTERV plate fin with deluge augmented cooling (horizontal configuration) (Figure 10)
- the separate channel augmented tower (SCAT); a Curtiss-Wright extruded tube with integral fins, augmented with water flowing internally through separate channels
- the augmenting ammonia condenser (AAC); Curtiss-Wright tube augmented with a separate water-cooled condenser close-coupled to a conventional wet tower (Figure 11).

The cost estimates of the five concepts summarized in Table 5, and the four ammonia systems in Table 6 indicate that the comparable capital cost, i.e., the capital cost of the cooling system plus the capitalized operating cost (based on a fixed charge rate of 18 percent), of the ammonia dry/wet concept are projected to about 38 percent less than the integrated dry/wet system. The absolute cost values are time- and site-dependent, but these results do show the cost ranking of the systems.

These results have led PNL to conclude that a significant incentive does exist to carry out a demonstration of the ammonia system and that the demonstration should include augmented cooling using both the deluge approach and the augmenting ammonia condenser. The criterion for the present selection is that, of the new systems studied sufficiently to develop an adequate technological base, they represent the most promising concept from the standpoints of:

- projected total evaluated cost of the developed system (which includes both capital cost of the developed system

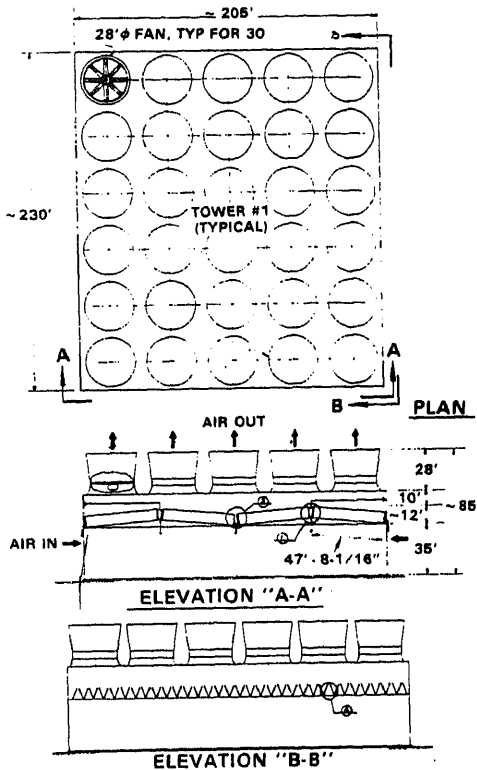


FIGURE 10. HÖTERV Plate Fin with Deluge for Dry/Wet Cooling Using Ammonia

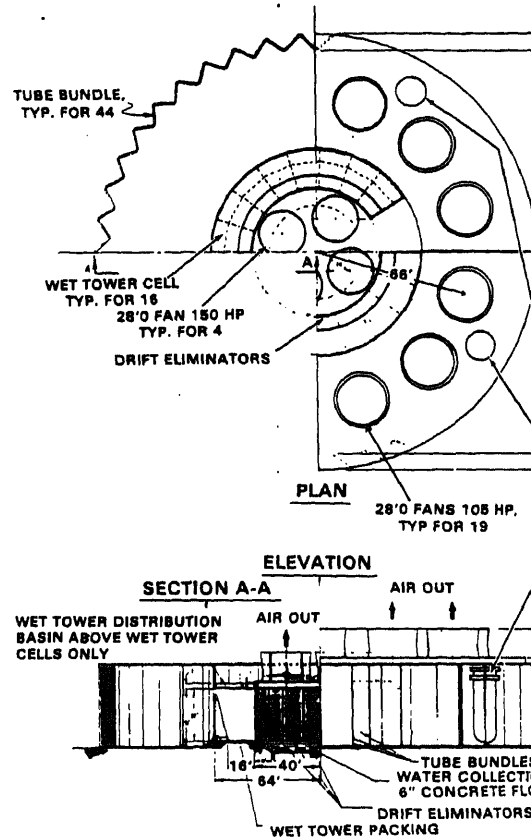


FIGURE 11. AAC Concept for Dry/Wet Cooling Using Ammonia

TABLE 5. Comparative Capital Costs for Five Dry/Wet Cooling Systems

System	Basic Capital Cost (106 \$)	Capitalized Operating Cost (106 \$)	Comparative Capital Cost (106 \$)
Integrated Dry/Wet	22.8	11.8	34.
Separate Dry/Wet	29.3	14.3	43.
Deluge/Finned Tube	28.9	9.5	38.
Plastic Tube	24.3	6.4	30.
Ammonia	23.2	5.3	28.

<u>Heat Rejection Concept</u>	<u>Estimated Capital Cost</u>	<u>Operating Cost</u>	<u>Capital Cost</u>
Integrated Dry/Wet	23.4	9.6	33.0
Vertical HÖTERV Tower	24.8	3.1	27.9
Horizontal HÖTERV Tower	21.6	3.1	24.7
SCAT Tower	21.5	3.0	24.5
Augmenting Ammonia Condenser	19.8	4.1	23.9

- water saving capability
- safety
- reliability
- acceptability by utilities.

New ideas are frequently suggested and the Dry Cooling Enhancement should continue to periodically survey the field to develop comparative for new concepts as their development progresses to the point that they be studied on a significant scale.

3.3 SELECTED CONCEPT FOR DEMONSTRATION

The ammonia heat transport system for power plant heat rejection fully in Reference 30) is functionally similar in many respects to the system in which the exhaust steam from the last stage of the turbine is directly to an air-cooled condenser. The principal difference is the use of a steam condenser/ammonia reboiler in which ammonia is "substituted" for steam as the medium for transporting heat from the turbine to the condenser (sink). In all respects the ammonia system, with vapor moving from the reboiler to the air-cooled condenser and liquid returning to the reboiler, function and respond to load changes in the same manner as the direct steam cycle.

Figure 12 is the schematic sketch. Exhaust steam from the last stage of the turbine is condensed in the condenser/reboiler located directly below the turbine. Instead of water circulating through the tubes, liquid ammonia is boiled as it is pumped through the tubes under a pressure set by the temperature in the condenser. The flow rate of ammonia is set to yield a quality emerging from the tube varying from 50 to 90 percent. This mixture is passed through a vapor-liquid separator from which the vapor goes to the air-cooled condenser, while the liquid is combined with the condensate from the dry tower and recycled back through the condenser/reboiler.

The vapor from the vapor-liquid separator flows to the dry tower where it is condensed. The driving force of the pressure difference between these two components is the pressure difference between the exhaust steam and the cooling water.

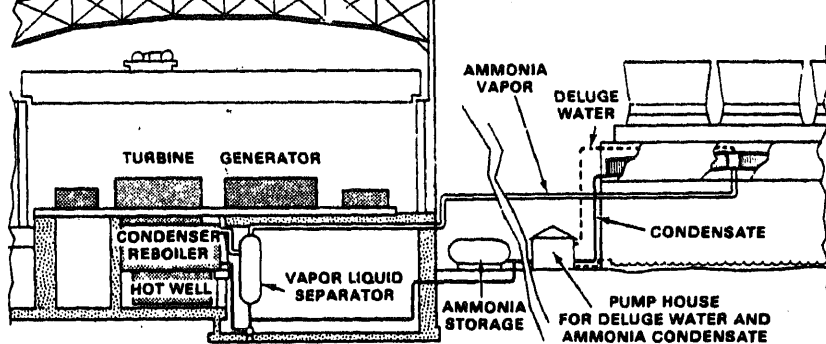


FIGURE 12. Dry/Wet System Using Ammonia

created by the temperature difference and the associated vapor pressure of the ammonia.

The vapor is condensed in the air-cooled (dry) tower. The ammonia vapor is condensed in either a vertical or horizontal tube arrangement emerging at the end header as a saturated liquid at essentially the same pressure as at the inlet header. The liquid flows to a liquid receiver and then out through a vapor trap by gravity to a transfer line and thence back to the condenser/reboiler. Isolation valves at the inlet and outlet manifolds of a tower section will provide a means of removing sections of the tower from service as may be required for maintenance or reduced cooling capability.

Further description of the concept as it will be tested in the ACT facility is given in Section 5.0.

3.4 SUPPORTING LABORATORY STUDIES

The design and construction of the ACT facility is being supported by technology development in four areas:

- air-side performance evaluation for the ammonia condenser in the dry cooling tower in both the all-dry and deluge mode.
- corrosion and deposition on the air-cooled condenser when operating in both the all-dry and deluge mode
- condenser/reboiler performance of the UCC/Linde tubes with surfaces modified for enhanced heat transfer
- condensation heat transfer of ammonia in long horizontal tubes.

The last two tasks are being done by UCC/Linde. The condenser/reboiler performance task is funded directly by EPRI. The last task has been done under

3.4.1 Air-Side Performance Evaluation

The Water Augmentation Test Apparatus (WATA) was constructed to test heat exchanger surfaces in both the dry and the deluge mode. Its primary role has been to investigate the effectiveness of performance augmentation by water flowing over the exterior surface. Inlet air to the loop is brought to the desired humidity and temperature, passed through the test core and exhausted to the outside. Energy to be transferred to the air is supplied by hot water circulated through the test core. A small fraction is withdrawn and put through a heater to provide the energy desired.

The augmentation water loop injects water onto the outside surfaces of the test core by the deluge injection system. Water not evaporated is collected at the base of the test core for recirculation and added to the system to make up for water lost by evaporation. The WATA apparatus is capable of orienting the core in any direction with respect to vertical so as to run with counter- or co-current flow of water over the surface and anything in between. Figure 13 is a photograph of the loop. A report⁽³¹⁾ has been completed which summarizes the heat transfer performance for the two candidate surfaces, the Curtiss-Wright and the HÖTERV. Both dry and wet performance was obtained for the HÖTERV surface. A theoretical analysis of the deluge heat transfer phenomena has been developed and published.⁽³²⁾ Other possible surfaces that have been suggested by manufacturers will be tested prior to their being considered for testing in the ACT facility.

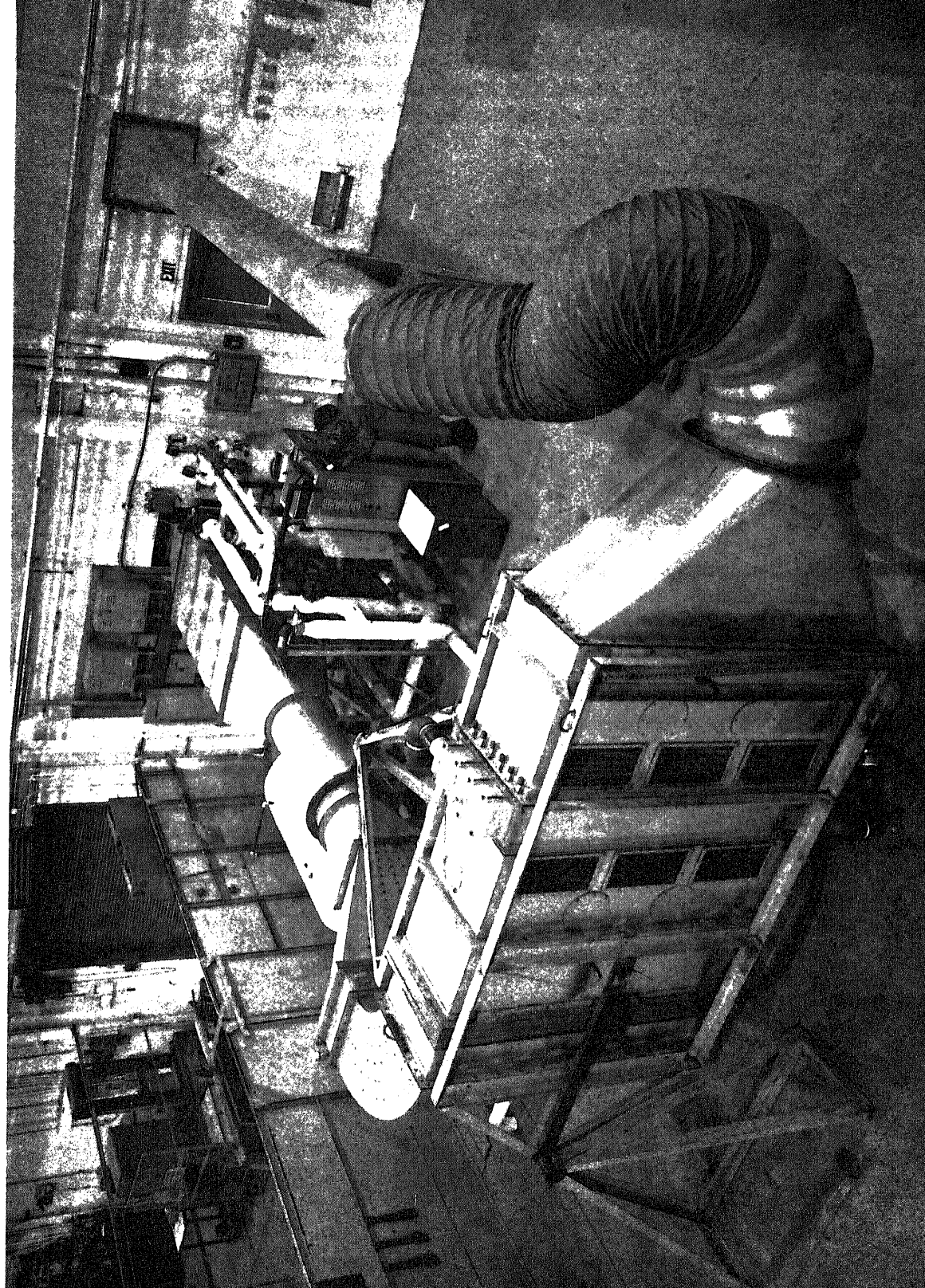
3.4.2 Materials Performance and Corrosion/Deposition on Air-Side Surfaces

In addition to the initial evaluation made of materials performance in large air-cooled heat exchangers, there has been a continuing program of material selection for dry tower application. D. R. Pratt⁽³³⁾ has reported on materials that can be successfully used with ammonia.

Water purity requirements to prevent scale deposition and corrosion during deluge operation has been treated theoretically in a paper by D. R. Pratt.⁽³⁴⁾ Initial results obtained on a small laboratory rig which puts a surface through multiple short cycles of water film and drying out on the heat exchanger surface has been reported by R. P. May,⁽³⁵⁾ et al. This work is continuing.

3.4.3 Condenser/Reboiler Performance (UCC/Linde)

Under EPRI sponsorship a small but complete loop including the reboiler/condenser, phase separator, dry tower, condensate return and recycle pump has been constructed and operated. Primary objective is to confirm single-tube data on the steam condensation and ammonia evaporation for the specially enhanced proprietary surface proposed by Linde for this type of service. No report is as yet available on this work.



in the air-cooled condenser has been studied experimentally at UCC/ under subcontract from Battelle during FY78. No significant effect sloping the tubes up to 15 degrees from horizontal nor of any hydraulic instability has been noted. A report is in preparation.

4.0 THE PAYOFF FROM DEMONSTRATION

To evaluate the benefit to cost ratio of the ACT project a study was made by Currie and Foley⁽³⁶⁾ to project the cost reductions of future savings that may accrue to users as the result of knowledge acquired from the project.

Elements of learning theory and the theory of technological diffusion were incorporated into a stochastic model that estimates a distribution of benefits from learning over a period of time and discounts these benefits back to the beginning of the demonstration project.

Three cases, of which two are discussed here, were evaluated in which the cost of electricity from state-of-the-art (SOA) dry/wet-cooled plants was compared with that from ammonia dry/wet-cooled plants. The variations were in the rate at which the cost savings from the use of the ammonia system are realized and the extent to which the demonstration influences the rate at which the ammonia system is used for dry/wet-cooled plants. Specifically the assumptions made in the two cases were as follows.

Case I

- The incremental cost of electricity from an SOA dry/wet plant does not change as more plants are built and is set at 1.86 mills/kWh for 20 percent wet-cooled.
- The incremental cost of electricity from an NH_3 dry/wet plant is 1.49 mills/kWh and does not change as more plants are built.
- NH_3 cooling use will not occur without demonstration.
- The demonstration has no effect on the growth rate of dry cooling.

The projected costs of electricity from SOA and ammonia dry/wet plants were derived from the costs for all-dry systems as evaluated in Reference 11, and the percentage reduction in incremental electrical costs going from all-dry to 20 percent wet/dry as evaluated in Reference 36.

Case II

- The incremental cost of electricity from SOA plants drops asymptotically from 1.86 mills to 1.57 mills (85 percent of current cost) after about 3 GWe of dry/wet plants are built.
- The incremental cost of electricity from NH_3 plants drops asymptotically from 1.86 mills (same as SOA) to 1.31 mills (85 percent of the currently projected cost for NH_3 -cooled dry/wet plants) after 3 GWe are installed.
- NH_3 cooling use will not occur without demonstration.
- The demonstration has no effect on the growth of dry cooling.

with which was associated a probability of attainment. In keeping with the projection that the "best guess" for installed dry/wet cooling by 2000 was 20 GWe, a probability distribution of attaining different market level fractions was developed which assigned the maximum probability to dry cooling ultimately attaining 12 percent of the market. However, the nature of the S-shaped function is such that only 4.1 percent of all station additions would be dry-cooled between 1985 and 2000.

The results of two cases studied are shown in Figure 14 and summarized below. (All costs corrected to 1978 dollar value, i.e., constant dollar costs.)

- Case I - The present worth of the gross benefits (to the year 2000) of demonstrating an NH_3 system with incremental electricity cost of 1.49 mills (20 percent wet) versus an SOA system with an incremental cost of 1.86 mills would have an expected value of \$145 million (at a 7-percent discount rate).
- Case II - The gross benefit of demonstrating an NH_3 system that initially has the same electricity cost as an SOA system (1.86 mills) but decreases to 1.31 mills versus a decrease to 1.49 mills for the SOA system would have an expected value of \$90 million (at a 7-percent discount rate).

These results are directly affected by the assumed amount of dry cooling installed by the year 2000 as shown in Figure 15; i.e., the greater the amount of technology developed as the result of the demonstration, the greater would be the benefits. A favorable benefit-to-cost ratio ranging from 5 to 1

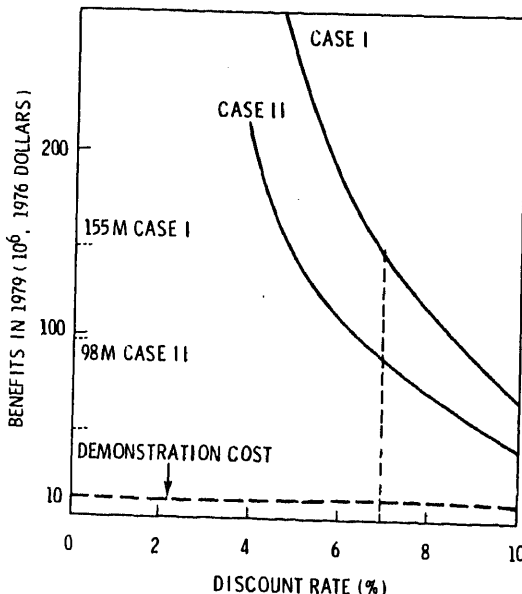


FIGURE 14. Benefits from Ammonia Cooling System Demonstration

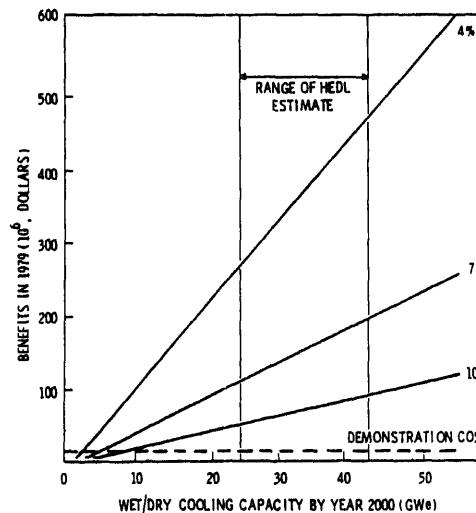


FIGURE 15. Benefits from Demonstration vs Assumed Dry Cooling Capacity (GWe installed capacity by the year 2000)

for the project is anticipated on the basis of this study if indeed 20
of 20 percent wet/dry cooling is installed by the year 2000 as the result
a demonstration which is projected at \$9 million. These results assume
demonstration is completed in 1983 and that a commercial system could be
line 2 years following completion.

The ACT facility is planned for the Kern Power Station of Pacific Gas & Electric near Bakersfield, California. This plant, normally held on cold standby, can devote one of two "house unit" turbines (approximately 6.0 MWe generating capacity each) exclusively to the advanced concept, thus affording a complete system demonstration. Because of the relatively high heat-rate of the unit, the heat rejection would be from condensation of up to 60,000 lb/hr of steam, equivalent to the heat rejected from approximately a 9.5-MWe plant of typical efficiency.

In the conceptual design⁽³⁷⁾ of the facility, shown schematically in Figure 16 and pictorially in Figure 17, the existing condenser for this unit will be bypassed and the exhaust steam will be routed to an ammonia reboiler/steam condenser located outside and immediately adjacent to the power plant building.

The condenser/reboiler will be a return flow shell-and-tube unit with condensing steam on the shell side and forced-circulation evaporating ammonia in the tubes. It will be a deaerating type with integral hot well. The tube will be fabricated of aluminum with an interior coating of the Linde "PBS" material. Tubes in the deaerating section will be stainless steel.

The ammonia vapor will be condensed in an induced draft, direct condensing cooling tower. The tower will be provided with two sets of heat exchangers of different types: 1) the HÖTERV plate fin-tube heat exchanger and 2) the Curtiss-Wright "chip-fin" heat exchanger. When operating with either heat exchanger sets, the tower will have a "dry" design capacity of 61.2×10^6 Btu/hr when operating with 125°F ammonia and with an ambient temperature of 55°F.

When ambient temperatures exceed 55°F, the tower capacity will be water augmented. When the HÖTERV system is in service, the augmentation will be accomplished by deluging the vertical fins of the heat exchanger sections. When a section is deluged, the fins of that section will be covered with a continuous film of water. The heat transfer to the air will occur by a combination of two mechanisms. The first mechanism is the convection of sensible heat to the air from the surface of the thin water film. The second mechanism is the transfer of latent heat by evaporation from the surface of the film. Since the film is continuous, deposition of minerals is unlikely because there is no dryout on the surface. During conversion from the wet to dry operation, the heat transfer surfaces are rinsed with zero-hardness water to limit the possibility of deposition during the ensuing dryout. Generally, the number of heat exchanger sections being

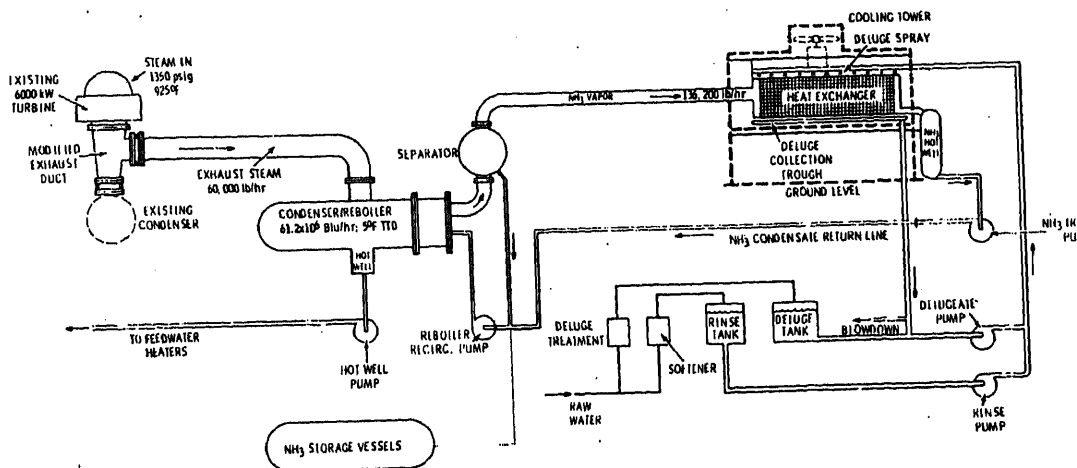
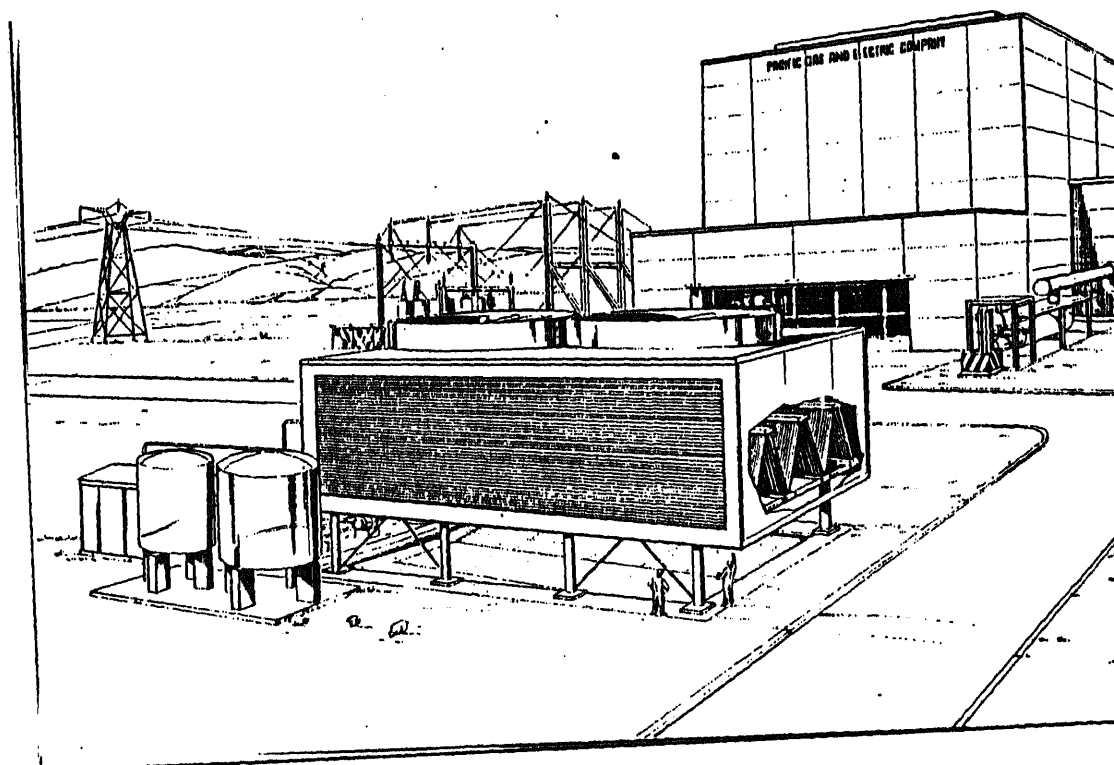


FIGURE 16. Schematic Process Flow Sketch, Advanced Concepts Test Facility



will be accomplished through the use of a water-cooled, shell-and-tube ammonia condenser. This condenser will be designed to condense 30 x of ammonia at 125°F. It will be cooled by means of recirculating cooling water from the existing plant cooling towers. The quantity of ammonia supplied to the augmentation condenser will be regulated to limit ammonia system pressure to some preset value.

5.1 PROJECT SCHEDULES

Studies to date have indicated that installation of many dry/cooling systems is inevitable but not immediate. As discussed in Section 4, the combined factors of uncertain growth rate of power needs, available alternatives (e.g., seawater cooling in California) and societal pressure to regulate water use contribute to the uncertainty of dry cooling predictions. For the demonstration project to have the greatest impact, it should influence the type of system constructed in the early years of the growth. EPRI has concluded that in order to meet the anticipated needs of the utilities, large scale testing of the ammonia system should begin now. Consequently, the design and construction project for the facility is proceeding under their sponsorship. PNL is managing the project with design and construction project management subcontracted to an A/E firm. Selection is in process and will be based primarily upon the experience and performance record of the organization in both large power plant projects and the design/construction of ammonia plants. Union Carbide/Linde will work closely with PNL both in an advisory capacity and to provide design of the major components - the condenser/reboiler.

Significant milestones in the project are:

- Completion and approval of the preliminary design and construction cost estimate July 1980
- Completion of detailed design January 1981
- Completion of construction February 1982
- Completion of acceptance testing and start of the testing program April 1983

5.2 INTEGRATION WITH INDUSTRY

Consistent and meaningful input from industry is essential to successful commercialization. Such input will be received from the utilities through the EPRI Steering Committee for Heat Rejection Program. It is planned that additional input will be sought from representatives of supporting

project participants to review programs and provide guidance. The involvement of component manufacturers is being sought through the procurement process. A Program Opportunity Notice has been sent to more than 15 manufacturers outlining the scope and timing of the project and inviting them to qualify for receiving RFQs for the heat exchanger modules by providing essential data on the performance and projected cost (in a mature competitive market) of their proposed surface. Response has been received from at least two manufacturers, in addition to the two primary suppliers. The projected cost-effectiveness of the proposed surface for a large (1000 MWe) power plant will be weighed along with their bid to supply the test heat exchangers.

5.3 PROJECT FUNDING

The ACT project was originally planned to be part of the DOE Dry Cooling Enhancement Program. This program also included general technology tasks directed toward the development of other advanced heat transfer surfaces applicable to large-scale testing, identification of water chemistry limits to prevent scaling and corrosion, and comparative evaluations of other advanced concepts of dry (dry/wet) cooling. Additional funding from EPRI and other sources was anticipated, particularly during the operating phase of the project. Several factors have changed these plans so that now EPRI has assumed the lead role in the design and construction of ACT. Additional funding from DOE, other agencies and select utilities is still being sought to continue the technology support program and to provide for facility operations.

ACKNOWLEDGMENTS

The DCE Program at PNL has been under the direction of Dr. W. E. Savage and Ira Helms of DOE/ASMP. Their guidance, assistance and interest has been a key factor in the development of the ACT project.

The accomplishments of the DCE Program have been the result of an interdisciplinary effort of staff principally from the Engineering Physics, Materials and Energy Analysis Departments. Principal contributors have been R. T. Allemann, Daniel Braun, David Braun, J. W. Currie, D. W. Faletti, J. D. Goodenough, P. L. Hendrickson, A. B. Johnson, D. K. Kreid, R. P. May, L. J. MacCowan, H. L. Parry, R. D. Tokarz, L. E. Wiles, and F. R. Zaloudek. Their dedicated efforts are gratefully acknowledged.

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WASTE HEAT MANAGEMENT IN THE ELECTRIC POWER INDUSTRY:
ISSUES OF ENERGY CONSERVATION AND STATION OPERATION
UNDER ENVIRONMENTAL CONSTRAINTS

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Introduction

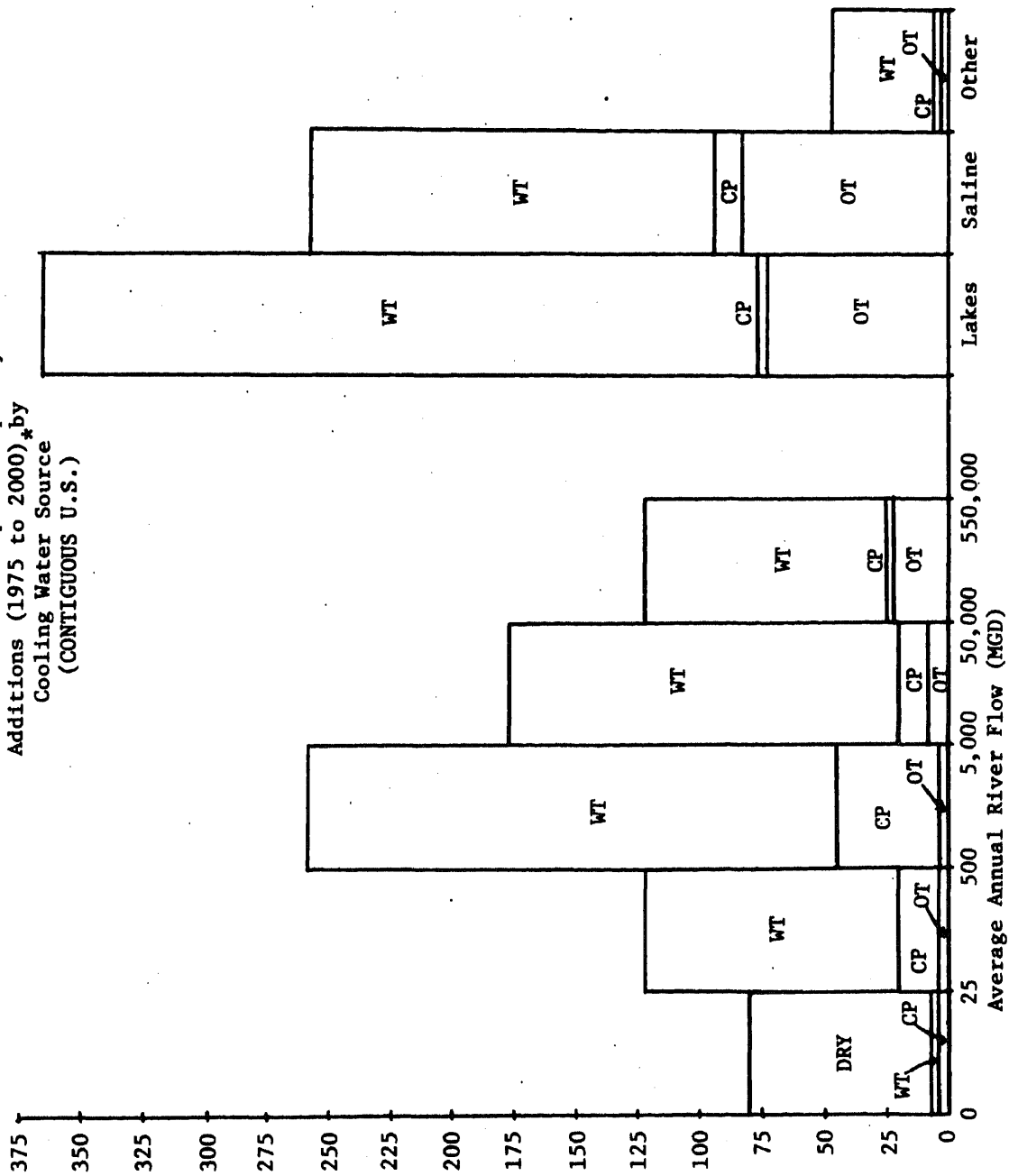
Between the years 1975 and 2000, it is expected that the demand for electricity will increase by 150 to 350% [1,2]. This will require the construction of between 500×10^3 and 1500×10^3 MW of new capacity, the vast majority of which will be supplied by large steam-electric facilities. While the increasing demand for electricity clearly documents its attractiveness to the user, the construction of so many plants raises significant questions concerning cost, environmental impact and natural resource requirements (in particular fossil and nuclear fuels, and water). The research program at MIT focuses on a topic where these issues come together: the selection of power plant cooling systems.

Before discussing the research program, it is worthwhile to consider some energy-related projections. Table 1 presents data on present (1975) and anticipated (year 2000) electrical capacity organized by cooling system type [2]. Figure 1 shows how the added capacity (difference in the figures plus anticipated retirements minus upratings) will be distributed according to the size and type of cooling water body. This data brings out several interesting points.

First, the use of once-through cooling, which accounted for approximately 63% of the cooling in 1975, will account for only 16% by 2000. This change can be attributed to several factors, including the decreasing availability of suitable sites on large bodies of water, and the influence of state and federal water quality standards which discourage use of once-through cooling. While once-through cooling will still be the second most popular system, the new sites employing this mode will be located almost exclusively on the Great Lakes and coasts.

Second, the vast majority of closed cycle cooling, as presently proposed will be by natural and mechanical draft evaporative (wet) towers. Other forms of evaporative closed cycle cooling such as on- or off-stream cooling ponds or various types of mixed modes show relatively minor increases due largely to complexities governing their design (as compared to modularized construction of mechanical draft towers) and due to the endorsement of wet towers by EPA as "Best Available Technology."

Figure 1
Distributions of Proposed Capacity
Additions (1975 to 2000)* by
Cooling Water Source
(CONTIGUOUS U.S.)



WT = Wet Towers, OT = Once Through, CP = Cooling Ponds, DRY = Dry Towers

Table 1
Present and Future Steam-Electric Generating
Capacity by Cooling System Type¹

	(Capacity in MW)	
	<u>1975</u>	<u>2000</u>
Once Through	249,000	322,000
Cooling Ponds	54,000	218,000
Wet Towers	79,000	1,312,000
Dry Towers	28	67,000
<u>Combination</u>	<u>10,000</u>	<u>37,000</u>
Total	392,000	1,956,000

¹ Source USWRC, Energy and Related Water Requirements, Appendix H, April 1977, Table A-3, p.A-27.

The ability to design and predict the performance of once-through and wet cooling tower systems is well developed as a result of intensive research, development and operating experience over the past decade. In contrast, the use of dry and wet/dry towers, cooling ponds and mixed modes have been constrained by design, performance and cost uncertainties. In addition, there appears to have been very few previous attempts to provide a common framework for optimal design, prediction of performance (in terms of efficiency and power availability) and cost evaluation for the entire spectrum of cooling system alternatives.

The research program at MIT is an attempt both to provide such a common framework and to examine modes of cooling presently attended by performance uncertainties. The research program has been divided into five parts. The first three deal with the cooling system alternatives described above including (1) the use of dry and wet/dry towers for closed cycle cooling, (2) the use of artificial (off-stream) ponds for closed cycle cooling and (3) the intermittent use of evaporative cooling towers to supplement once-through cooling for purposes of meeting environmental constraints. In part (4) the study, design codes for dry and wet/dry towers, and for cooling ponds are used with existing codes for once-through and evaporative towers to provide a comparison of economic, environmental and resource consumption trade-offs for these systems. Finally, in part (5), these results are used along with various scenarios of energy demand to estimate the incremental costs, and the water and fuel consumption, which would result from future thermal discharge controls.

It should be pointed out that these research activities, while related, are designed to be independent and not merely a series of components leading

Part I Design and Optimization of Dry and Wet/Dry Cooling Towers

Cooling systems for power plants located in arid regions must be designed to minimize water consumption. Because the use of dry cooling towers, either by themselves or in combination with wet towers, substantially increases both the capital and operating cost of a power plant, the economics of such systems must be carefully considered. In the present study several research areas that address this problem are being examined.

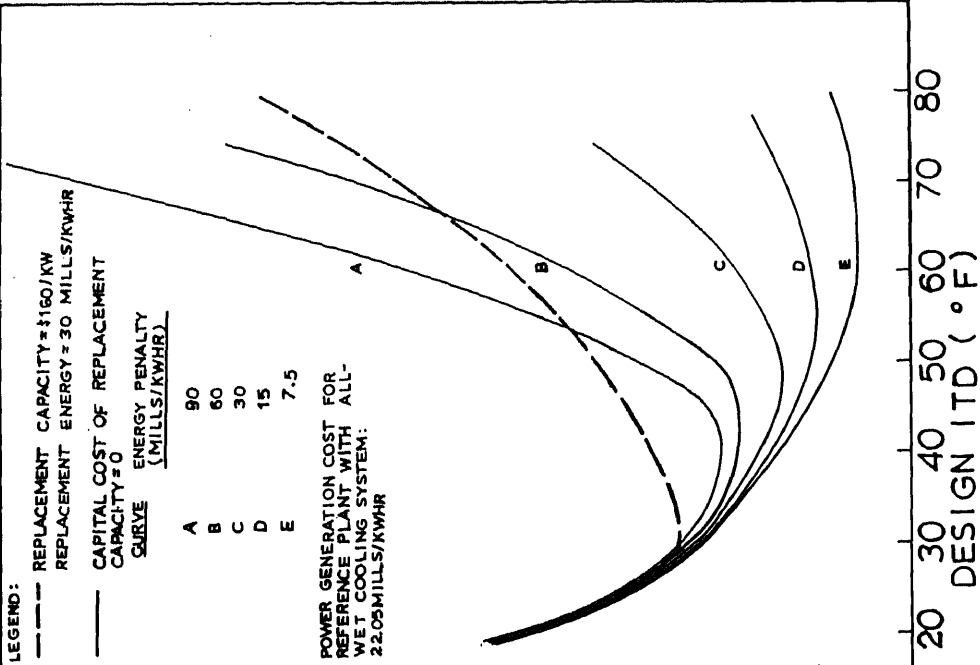
The interaction of cost and power plant performance has been carefully analyzed for the case of an all dry mechanical draft tower by refining an optimization program which was originally developed in the Mechanical Engineering Department at MIT [3,4]. The program considers ambient temperature variations throughout the year for the site in question. Rather than using predesigned dry modules, the module design is also optimized, e.g. by determining air velocity, tube length, etc., so that the average yearly cost of power generation of the plant-cooling tower combination is minimized. Recent refinements to the model include optimization of the surface condenser and the water distribution system between the condenser and the tower so that the optimum range and pipe sizes for the system can be determined.

A major economic penalty associated with the use of dry towers is the loss of generating capacity at high ambient temperature, especially for a utility with a peak demand during the summer. How to assess this penalty has been of concern to both utilities and tower designers. The present study explores various options for replacing lost capacity ranging from use of gas turbines devoted exclusively to the task to total replacement by purchase of electricity at elevated costs per kilowatt hour. The effect of each option on the economic optimization of the plant-cooling system has been documented. A major conclusion is that the optimal tower size can be significantly decreased, thus reducing both capital and total production costs if a utility is able to purchase peak power. (See Figure 2)

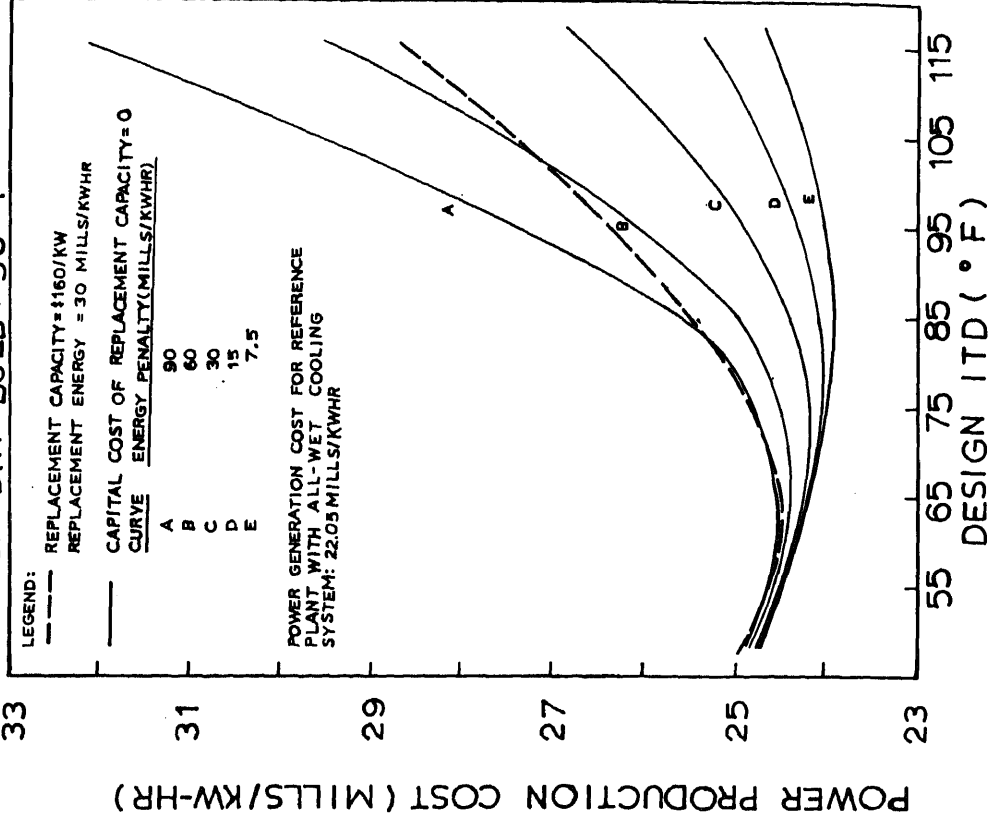
The optimization program has also been modified to facilitate examination of wet/dry systems. Evaluations have been performed to determine the minimum cost system for a given yearly water consumption constraint (See Figure 3). The optimization is performed in consideration of detailed tower and water distribution designs and methods of accounting for lost capacity. This approach differs from that undertaken by others, e.g. [5], who base their optimization on pre-designed tower modules.

Finally, a study of MIT's hybrid wet/dry system [6] is underway. This design uses a modified fill in essentially a wet cooling tower to increase the ratio of sensible to latent heat transfer; in previous tests of the design, the heat transfer by evaporation has been reduced to forty percent (compared to roughly eighty percent for a conventional wet tower). Since the new design does not require a conventional dry surface, it should be less expensive than a conventional wet plus dry and in addition the reduced relative humidity of the exhaust air is always low enough to preclude the

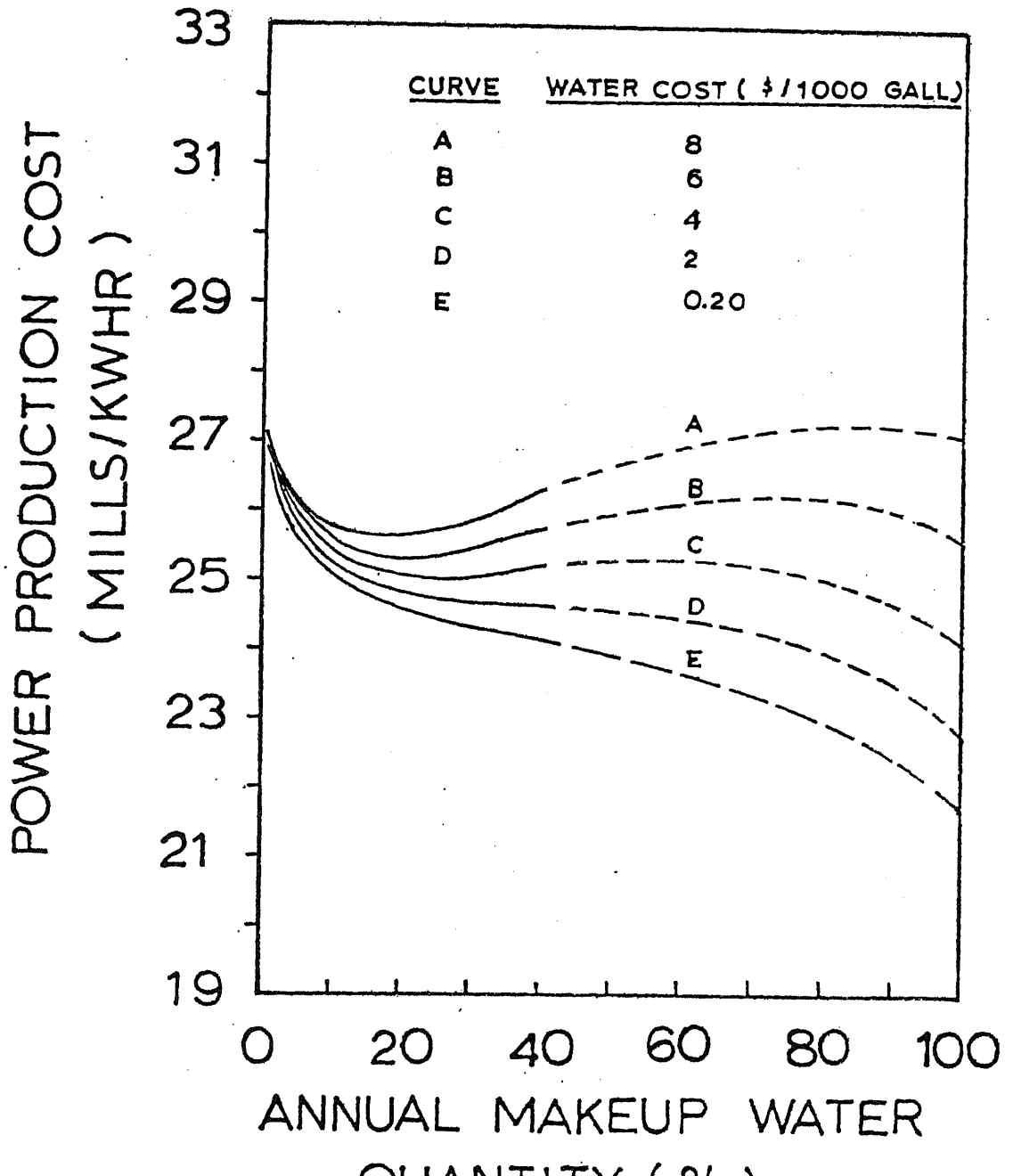
800-MWe FOSSIL PLANT TURBINE: CONVENTIONAL DESIGN DRY BULB: 50 °F



800-MWe FOSSIL PLANT TURBINE: HIGH BACK PRESSURE DESIGN DRY BULB: 50 °F



1200-MWe NUCLEAR PLANT



Tests of the system are also being carried out to determine the performance using new water distribution designs which will be much less expensive to fabricate and at the same time more reliable.

Part II Design and Optimization of Recirculating Cooling Ponds

Cooling ponds are large, artificially constructed, water bodies used for closed-cycle dissipation of power plant waste heat. While there are areas of the country where cooling ponds have been widely used (e.g. Texas and Illinois), their use has been restricted by the relatively poor state-of-the-art in predicting cooling pond performance (e.g. relative to that of wet towers). This difficulty is created by the complex circulation patterns found in a pond and by the highly transient response of a pond to time-varying meteorology. As a consequence of past difficulties in simulating performance of a given pond, there have been few established guidelines for the design (optimization) of ponds. Existing guidelines are based on very simple, usually steady state, hydrothermal models.

Over the past years the Ralph M. Parsons Laboratory of the Department of Civil Engineering at MIT has been engaged in the development and application of mathematical models to study the hydro-thermal performance of cooling ponds and lakes [7-10]. The object of the present effort has been to synthesize information from these models in order to develop a rational cooling pond design methodology. The specific tasks which have been undertaken are as follows:

A computer program and user's manual to simulate the transient performances of cooling ponds of different classifications including deep, shallow dispersive, and shallow recirculating has been completed. (The development of the individual sub-models and the initial integration of the sub-models was performed under different sponsorship. It was necessary, however, to complete the integration as well as to make modifications for the present purposes).

Using these transient models, predicted pond performance (statistical distribution of intake temperatures) was evaluated for a range of pond design parameters including range across the condenser, pond area, depth, and pond shape (density of baffles). The evaluation was based on one year of meteorological data from Moline, Illinois.

For purposes of preliminary design, a quasi-steady model was developed to correspond to the transient model for the most efficient design - the shallow dispersive pond. Input to the quasi-steady model consists of time-averaged values of equilibrium temperature and surface heat loss coefficient. The appropriate averaging interval is selected as a function of pond depth to represent the thermal inertia inherent in the transient model. By assembling the averaged meteorological variables into a cumulative (bi-variate)

The various operating and capital costs which influence the economy of power plants cooled with ponds were considered. These costs include primarily, circulating water pumps, land purchase and preparation, water consumption and lost generating capacity. Based on their simulated performance, the total production cost of each design was expressed as a function of these costs, in order to allow the evaluation of optimal designs. Figure 4 presents an example illustrating cooling pond costs versus land area for various land costs.

Part III Development of Control Technologies for Supplementary Cooling

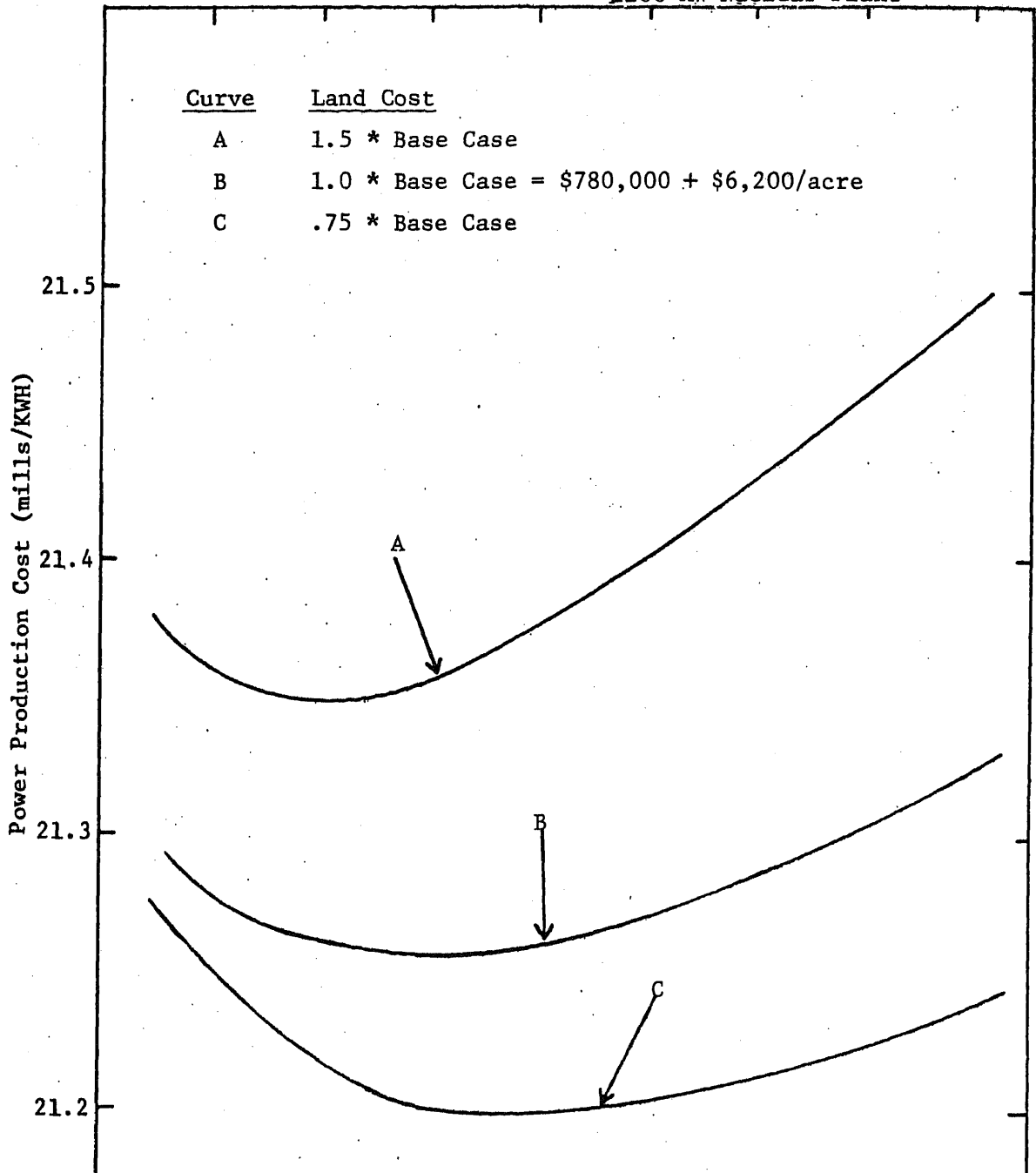
At sites where the supply of cooling water is sufficient for once-through cooling supplementary cooling systems (e.g. cooling towers) may be required in order to meet environmental constraints on induced water temperature changes. At many of these sites it may be feasible to design a mixed mode cooling system which operates in either the open, closed, or helper (once-through but with use of the cooling tower) modes. Such systems may be particularly economical where the need for supplementary cooling is seasonal or dependent upon other transient factors such as streamflow. With a mixed mode system, the use of cooling towers on either the helper or closed mode would be based upon real-time continuous measurements of water temperatures in much the same way as supplementary control systems for air quality control respond to ambient monitor readings.

The design and operation of mixed mode cooling systems involves a number of issues, all of which directly influence the loss of net generating capacity resulting from the use of cooling towers. First, the design of open cycle components of the condenser cooling system determines the limiting environmental conditions for open cycle operation. Second, the cooling tower design must reflect a balance between the capital cost of tower construction and the loss of net plant capacity during tower operation. Third, the location, operation, and interpretation of the temperature monitorings will be major factors in determining the frequency of cooling tower use. Of particular importance in this regard is the influence of natural temperature variations which may mask the true impact of plant operations. Finally, the specification of the environmental temperature standard itself will directly affect the percentage of time cooling tower use is required.

The design and operational issues detailed above have been examined in the context of a case study involving TVA's Browns Ferry Nuclear Plant. A large quantity of available site-specific data reflecting both pre-operational and post-operational conditions has made possible realistic simulations of plant operation and investigation of the sensitivity of plant capacity to design and operational parameters. Figure 5 shows such a simulation. The most important findings of the study are:

- (1) The capability to switch cooling modes results in only 10% of the capacity losses experienced by a totally closed system.

1200 MW Nuclear Plant



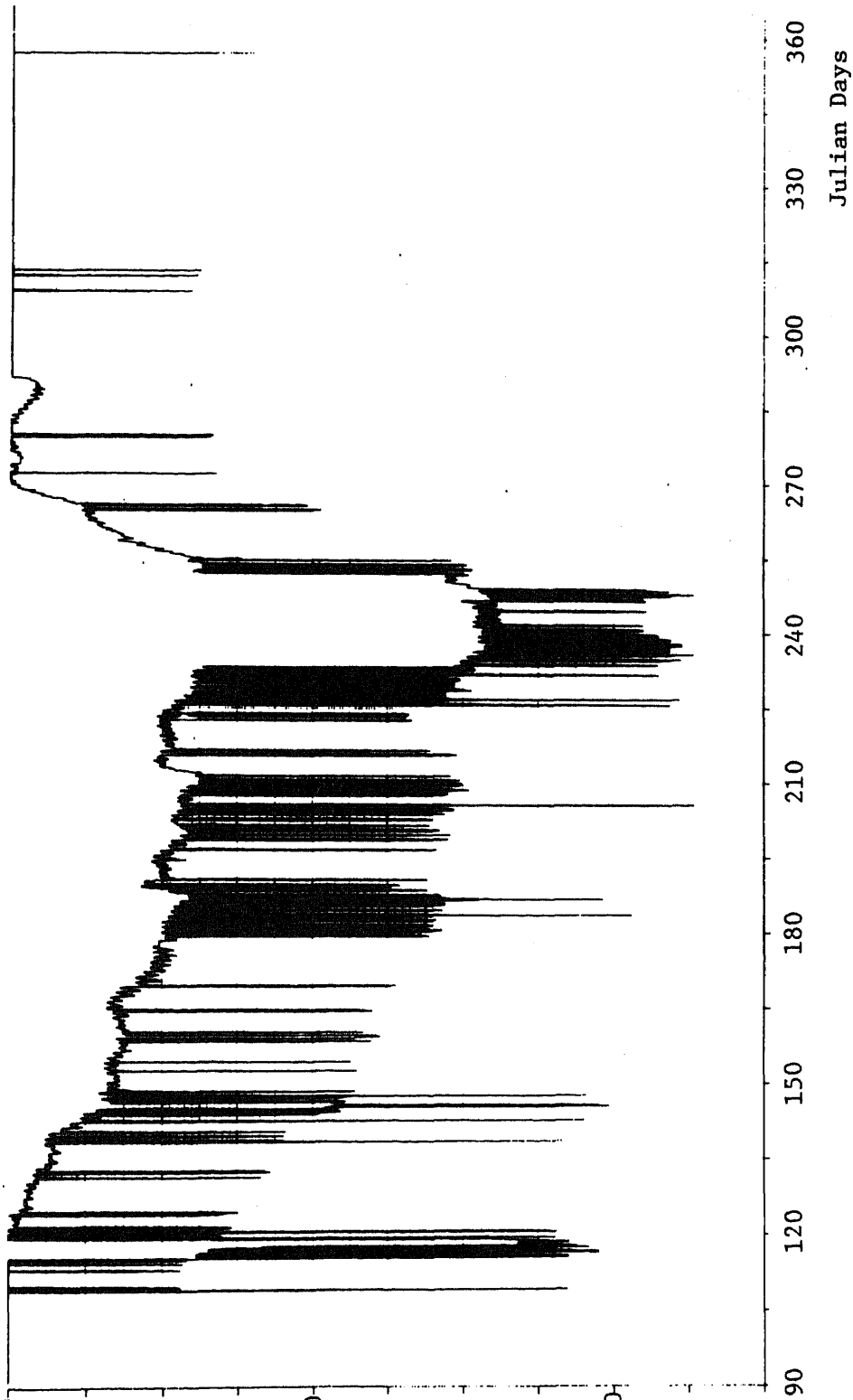


Figure 5 Example of Power Output Using Optimal Mixed Mode.

increase in lost capacity. Compared to the influence of the environmental standard, changes in plant design, such as cooling tower size or open cycle diffuser mixing, have significantly less influence on plant capacity losses.

- (3) About one third of the capacity loss incurred using a mixed mode system is the result of natural temperature variations that are interpreted as plant induced effects by the monitoring system. This unnecessary loss may be cut in half by the use of a predictive model for natural temperature variations developed by this study. Further reduction may be obtained by spatial and temporal averaging of temperature monitor measurements.

Part IV An Environmental and Economic Comparison of Cooling System Designs for Steam-Electric Power Plants

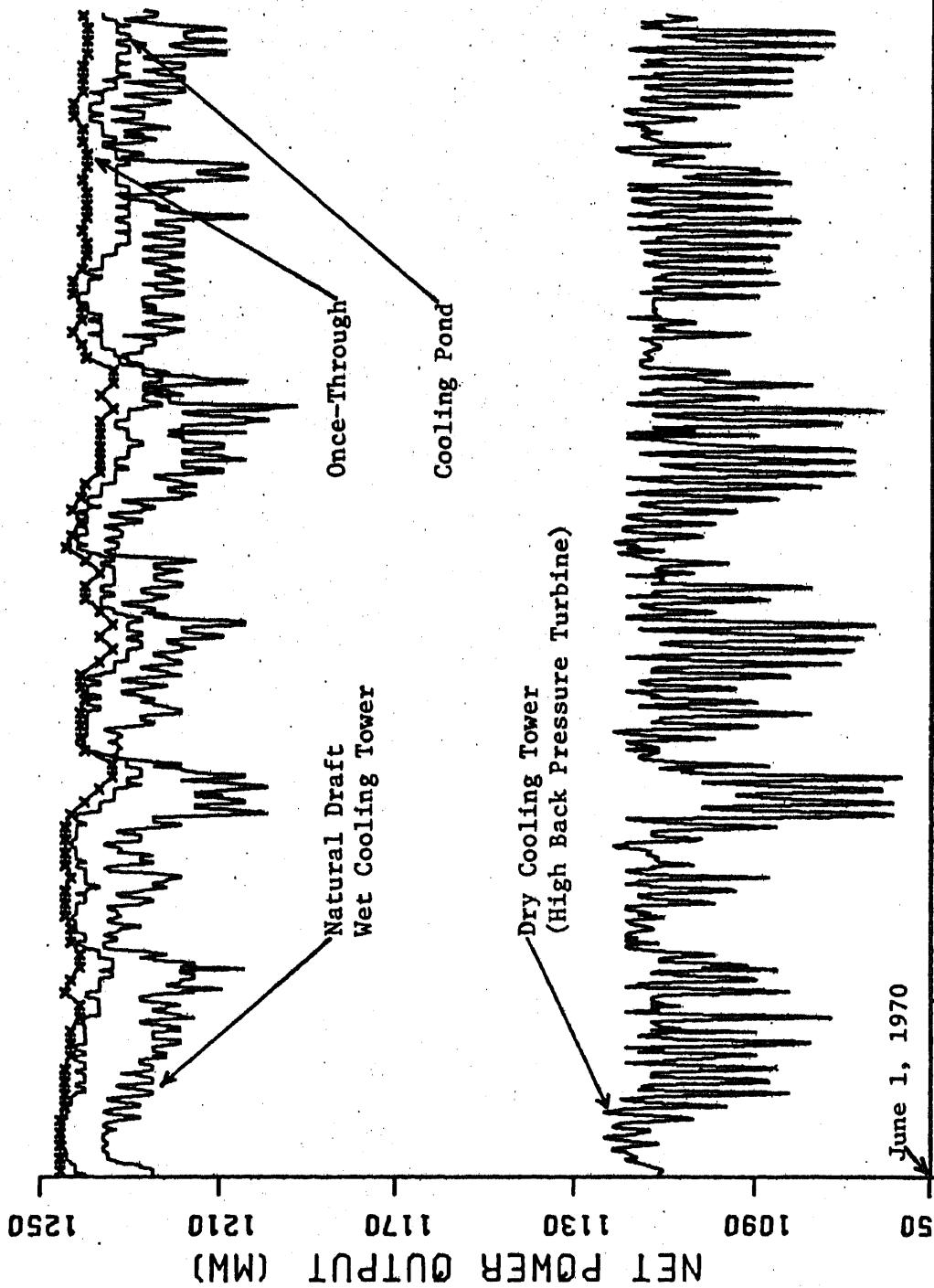
The engineering research efforts on cooling ponds and dry towers generated information that allows a comparison with other cooling system types — specifically once-through systems and both natural and mechanical draft wet towers. Such a comparison was made for a hypothetical 800 MWe fossil station and a 1200 MWe nuclear station located at a midwestern site on the Mississippi River. Design and simulation codes for cooling ponds and dry towers along with similar codes for open cycle and evaporative towers were used to establish optimally-sized cooling systems of each type based on a 10 year cumulative distribution of the appropriate meteorological and hydrological data. For once-through cooling, design options ranging from a surface discharge canal (least cost, greatest thermal impact) to submerged diffusers of different lengths and discharge velocities were evaluated. Figure 6 shows a simulation of power output during summer months for a station using four different cooling systems.

The cooling systems were then compared for a range of economic parameters including:

- capital cost of the power plant
- cooling system capital cost
- fuel cost
- cost of water consumption and water treatment
- cost for replacement capacity and for replacement energy
- capacity factor
- annual fixed charge rate

The comparison included present-valued incremental costs, power production costs, fuel and water consumption, and various environmental impacts. Table 2 shows part of this comparison for the case of the nuclear plant.

Figure 6 Cooling System Transient Simulation
(summer 1970)



	Once-through: Surface Canal	Once-through: Multiport Diffuser	Cooling Pond	Natural Draft Wet Tower	Mechanical Draft Wet Tower	Mechanical Draft Wet/Dry Tower *	Mechanical Draft Dry Tower
Power Production Cost (mills/KWH)	20.93	21.13	21.26	21.63	21.56	24.45	26.21
Cooling System Capital Cost (\$ x 10 ⁶)	18.48	27.31	27.53	34.46	27.52	73.49	108.59
Total Fuel Cost ** (mills/KWH)	4.87	4.88	4.91	4.97	4.96	5.29	5.64
Maximum - Minimum Power Production (MW)	13.3	13.5	28.8	44.6	37.2	60.0	81.1
Water Withdrawal Rate (cfs)	1500.	1500.	41.2	38.7	33.7	10.1	~
Water Consumption (cfs)	16.8	16.8	27.7	27.8	23.5	7.1	~

a) 1200 MWe Nuclear Plant

	Once-through: Surface Canal	Once-through: Multiport Diffusers	Cooling Pond	Natural Draft Wet Tower	Mechanical Draft Wet Tower	Mechanical Draft Wet/Dry Tower *	Mechanical Draft Dry Tower
Power Production Cost (mills/KWH)	21.62	21.76	21.84	22.03	22.05	23.81	24.43
Cooling System Capital Cost (\$ x 10 ⁶)	11.89	16.20	14.57	15.33	13.84	36.92	48.08
Total Fuel Cost ** (mills/KWH)	7.92	7.93	7.94	8.00	8.03	8.11	8.53
Maximum - Minimum Power Production (MW)	12.8	12.9	20.4	23.8	18.6	26.0	43.7
Water Withdrawal Rate (cfs)	840	840	18.9	16.1	14.8	4.4	~
Water Consumption (cfs)	7.7	7.7	12.5	11.6	10.6	3.2	~

b) 800 MWe Fossil Plant

Part V Regional Implications Involving the Choice Between Open and Closed Cycle Cooling

An examination of Figure 1 indicates that most new generating stations are slated to use wet cooling towers, despite the fact that many plants will be located on coastal, Great Lakes or large river sites. According to a recent UWAG study [11], over one half of these stations are proposing wet towers only because of state or federal water quality laws while an additional one-third have chosen wet towers for a combination of reasons including environmental regulations.

The large projected decrease in the use of one-through cooling (relative to wet towers) invites a number of questions concerning costs, environmental impact and natural resource requirements. In part (5) of this study several of these questions are addressed by estimating, regionally, the financial, energy and fresh water savings which could occur if more new plants were to employ once-through cooling than current plans suggest.

A first step was to estimate required new generating capacity for each of the 18 U.S. Water Resources Council (WRC) regions through the year 2000, as a function of projected national energy demand. One estimate is based on data supplied by electric utilities for stations scheduled to be in operation by 1996, and extrapolated by the F.E.R.C. to the year 2000 [2]. Figure 1 is based on this data. Since this is generally regarded as a high estimate of demand (it corresponds to an overall energy demand of 163 quads in 2000), a lower estimate (corresponding to 136 quads, or about two-thirds of FERC's projected growth) has been derived from ERDA forecasts [12].

For each of the two energy demand scenarios, the percentage of plants which could utilize once-through cooling was estimated. A base case, designated Scenario 1, refers to the cooling systems reported by FERC [2]. Other scenarios of once-through cooling capacity are based on maximum allowable temperature rises (defined by minimum streamflows or specified surface areas for lake or coastal sites), historical patterns of cooling system selection, or both. Table 3 shows the percentage of new plants which could employ once-through cooling for each of five different scenarios based on the high energy demand.

The cooling system design codes which were assembled in part (4) of this study were used to evaluate mechanical draft wet towers and open cycle systems in terms of cost, water, and fuel consumption. Evaluations were made for each of the 18 WRC regions taking into consideration regional variations in cost and meteorology. The evaluations were combined with the scenarios of energy demand and once-through cooling availability to provide regional estimates of cost and resource consumption for each scenario. By

ERC Region	Capacity Expansion By Region 1975-2000 GW	Scenario				
		I	II	III	IV	V
1	45	25.3	67.1	91.0	75.6	100.0
2	141	13.9	42.1	59.0	66.4	94.1
3	333	11.2	39.3	26.0	57.9	64.5
4	132	7.0	70.1	81.0	100.	100.0
5	173	3.2	16.7	62.0	24.6	24.6
6	35	2.6	15.2	61.0	47.8	47.8
7	118	0.9	13.4	78.0	28.3	33.0
8	73	42.5	61.1	100.0	71.8	88.8
9	0	0	0	0	0	0
10	81	8.2	24.8	54.0	33.1	33.1
11	80	8.2	13.9	36.0	28.5	28.5
12	157	27.3	38.8		60.3	60.8
13	4	0	0		0	0
14	14	0	10.8		21.5	21.5
15	16	0	4.7		10.6	10.6
16	20	0	5.0		5.0	7.7
17	35	3.7	43.9		79.1	84.5
18	46	43.1	47.2	78.0	77.3	100.0
guous S.	1,504	12.9	35.6	54.0	54.0	60.9

Percent of Planned Capacity (1975-2000) Able to Employ Once Through Cooling, By Region
for the High Energy Demand Case

concerning thermal discharges not an overriding concern.

Certainly, arguing for a move back to a policy of liberal use of once-through cooling, without careful scrutiny of the environmental consequences of such a move, is not in keeping with the nation's commitment to minimize environmental degradation. Nevertheless, one can characterize the costs, in terms of dollars, water consumption, and energy consumption, of a decision to phase out once-through cooling, and as Table 4 indicates, these costs are not insignificant.

Incremental Change in Units of:

Region	Annual Cost (Millions of 1977 Dollars)	Net Fresh Water Consumption (MGD)	Net Energy Consumption 10 ¹² BTU/yr
1	143	259	29
2	284	678	53
3	191	223	39
4	448	374	90
5	387	374	76
6	97	80	21
7	399	366	89
8	193	187	47
9	0	0	0
10	125	125	32
11-17	325	428	69
18	82	223	15
Total U.S.	2,674	3,317	560

Table 4 Incremental Effects in Year 2000 of a Change from Scenario #1 to Scenario #3 for the High Energy Demand Case.

- (2) U.S. Water Resource Council, Energy and Related Water Requirements, Appendix H, April 1977.
- (3) Andeen, B.R., and L.R. Glicksman, "Computer Optimization of Dry Cooling Tower Heat Exchanges," ASME Winter Annual Meeting, N.Y., November 1972.
- (4) Andeen, B.R., L.R. Glicksman and W.M. Rohsenow, "Improvement of the Environmental and Economic Characterization of Cooling Towers, Part I: Optimized Design Program, Fluidized Bed and Non-metallic Heat Exchanges," MIT, Cambridge, MA, June 20, 1973.
- (5) Engineering and Economic Evaluation of Wet/Dry Cooling Towers for Water Conservation, United Engineers, November 1976.
- (6) Curcio, J., M. Giebler, L.R. Glicksman, and W.M. Rohsenow, "Advanced Dry Cooling Tower Concept," Technical Report No. MIT-EL75-023, MIT, Cambridge, MA, 1975.
- (7) Ryan, P.J., and D.R.F. Harleman, "An Analytical and Experimental Study of Transient Cooling Pond Behavior," R.M. Parsons Laboratory for Water Resources and Hydrodynamics, T.R. No. 161, January 1973.
- (8) Watanabe, M., D.R.F. Harleman, and J.J. Connor, "Finite Element Model for Transient Two-Layer Cooling Pond Behavior," R.M. Parsons Laboratory for Water Resources and Hydrodynamics, T.R. No. 202, July 1975.
- (9) Jirka, G.H., D.N. Brocard, K.A. Hurley-Octavio, M. Watanabe, and D.R.F. Harleman, "Analysis of Cooling Effectiveness and Transient Long-Term Simulations of a Cooling Lake with Applications to the North Anna Power Station," R.M. Parsons Laboratory for Water Resources and Hydrodynamics, T.R. 232, December 1977.
- (10) Jirka, G.H., M. Watanabe, K.A. Hurley-Octavio, D.F. Cerco, and D.R.F. Harleman, "Mathematical Predictive Models for Cooling Lake Design," to be published as R.M. Parsons Laboratory for Water Resources and Hydrodynamics Technical Report, 1978.
- (11) Utility Water Act Group, "Thermal Control Cost Factors - Status of Present and Planned Water Intake and Discharge Systems for the Electric Utility Industry: The Results of a Survey," submitted to the United States Environmental Protection Agency, June 1978.
- (12) Williamson, R.H., and E.J. Hanrahan, "Energy Modelling and Forecasting Program at ERDA," Washington, D.C., June 1976.

U.S. Principal Investigators

R. J. Haberski
Curtiss-Wright Corporation
J. C. Bentz
United Engineers and Constructors
J. L. Sonnichsen
Hanford Engineering Development Laboratory
Dr. Frank Moore
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In addition to support of the EPRI/EPA/DOE Battelle Pacific Northwest Laboratory technology development work on dry and dry/wet cooling, separately reported in the B. M. Johnson paper, the Division of Advanced Systems and Materials Production (ASMP) has supported several smaller supporting efforts in heat dissipation technology.

In cooling systems the ASMP Division has had several small study efforts for improving performance and cost of cooling systems. Earlier the Division supported exploratory work on new cooling system ideas at M.I.T.⁽¹⁾ (V-trough plate) including the estimation of the cost/performance of complete cooling towers using that idea.⁽²⁾ A second small program has been the evaluation of the cost improvement of using the Curtiss-Wright Multiple Channel Extrusion, Integral-Fin Concept in dry cooling systems for utilities.⁽³⁾

This concept is also being considered in the EPRI/DOE Dry and Dry/Wet Cooling Tower work at PNL.

Also, the ASMP Division has supported the development at HEDL of a computerized system for estimating water requirements of and water availability for power plants. This has been developed as a service to

(1) MIT EL 77-062, Advanced Wet Dry Cooling Tower Concept Performance Prediction

(2) A Preliminary Evaluation of a Parallel Flow Closed Circuit Wet/Dry Tower System. United Engineers and Constructors Contract E(11-3)2477.

(3) COO-4218-1 Conceptual Design and Cost Evaluation of a High Performance Dry Cooling System.

projections used in evaluating the overall cost benefits of the dry, dry/wet cooling tower program at PNL.

The last of the supporting studies to be discussed in this paper is an exploratory analytical/experimental effort at Cornell University to investigate the effects of wind on cooling tower performance -- especially of natural draft dry cooling systems where substantial adverse effects have been found for relatively low wind speeds.

The remainder of this paper is devoted to a description of three of these activities as follows:

1. The improved heat exchanger being investigated for DOE at Curtiss-Wright.
2. The HEDL power plant water program.
3. The Cornell University wind effects.

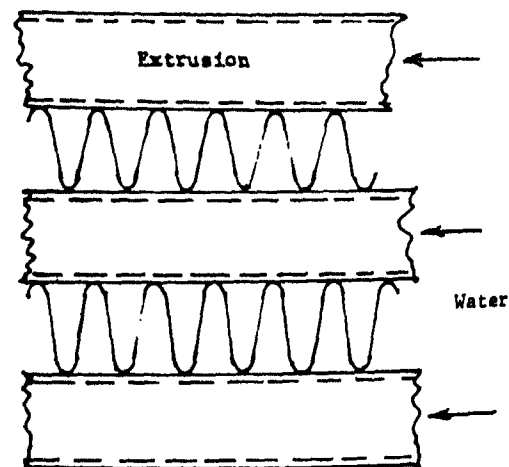
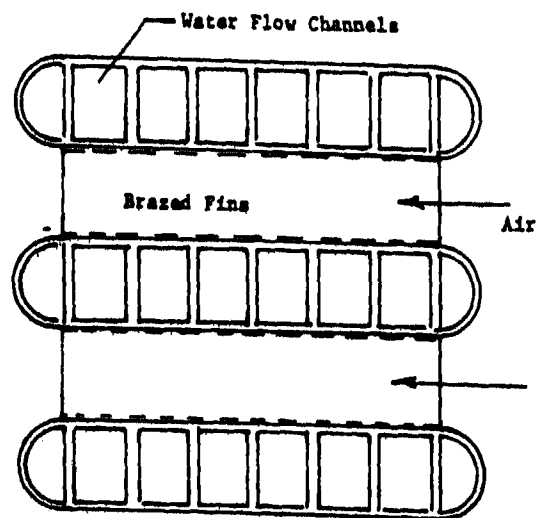
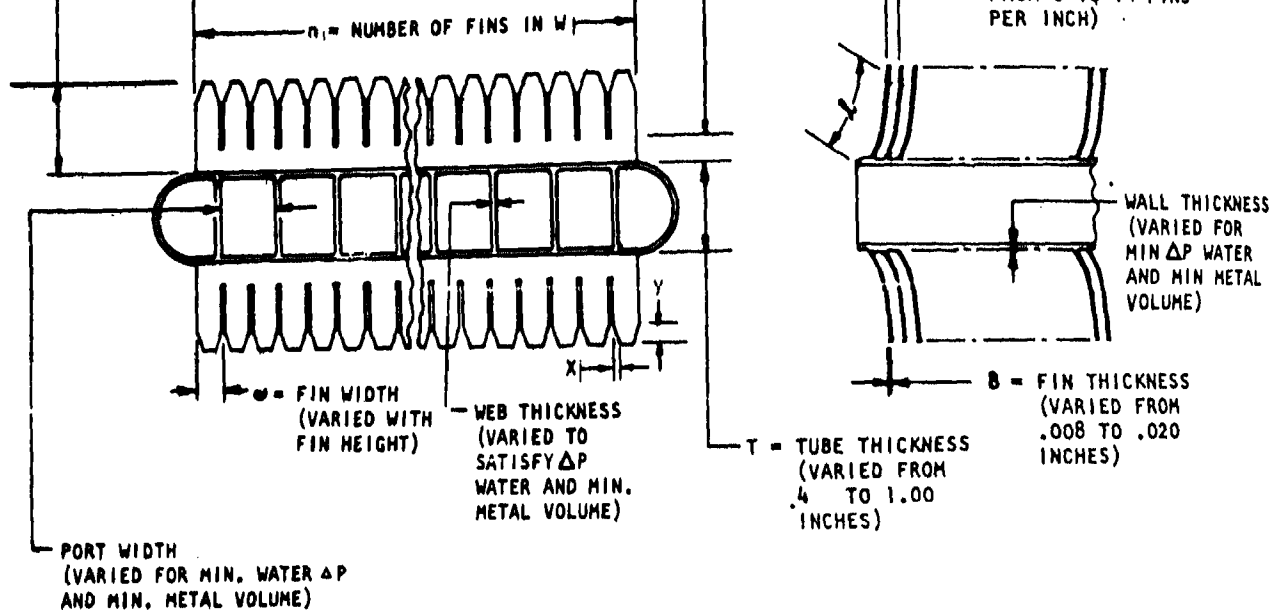
1. Improved Curtiss-Wright Heat Exchanger

Principal Investigators: R. J. Haberski, Curtiss-Wright Corp.
J. C. Bentz, United Engineers and Constructors

The objectives of this program were to establish a conceptual and preliminary design of a forced draft dry cooling system using high performance integral fin-tubes developed by Curtiss-Wright (CW) (see Figure 1), and to establish projected costs of this system for use in large electric power plants. The investigations reported herein are an extension of preliminary results previously reported.⁽⁵⁾ In the previous study, it was shown that significant performance and cost savings were potentially available with the use of the C-W advanced technology integral fin-tube heat transfer elements when used in forced or induced draft dry cooling towers. In the second phase of this study being reported here has been a more complete analysis of a complete tower

(4) HEDL TME 76-82, "Assessment of Requirements for Dry Towers."

(5) COO-2774-1, Engineering Analysis and Development of an Advanced Technology Low Cost Dry Cooling Heat Transfer Surface.



Similar Trans Concept

where C-W has been supported by United Engineers and Constructors, Inc. (UE&C) for the A&E aspects of the tower whose results are incorporated in reference 6.

This study was performed by C-W and UE&C as part of the overall DOE program to develop and demonstrate advanced concept dry cooling systems for large electric power plants. Preliminary conceptual design investigations, parametric fan and cooling module matching evaluations, cooling module design optimizations and performance verification testing were performed. Preliminary design, cost and installation investigations of the entire dry cooling system were performed by UE&C.

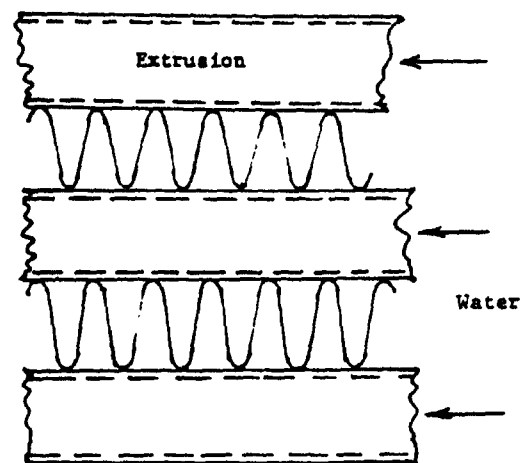
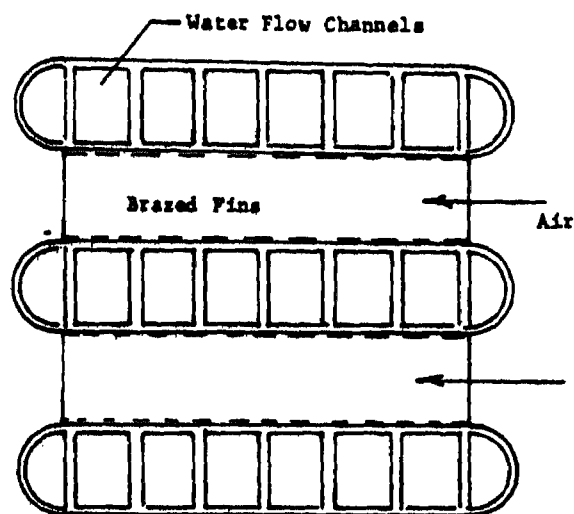
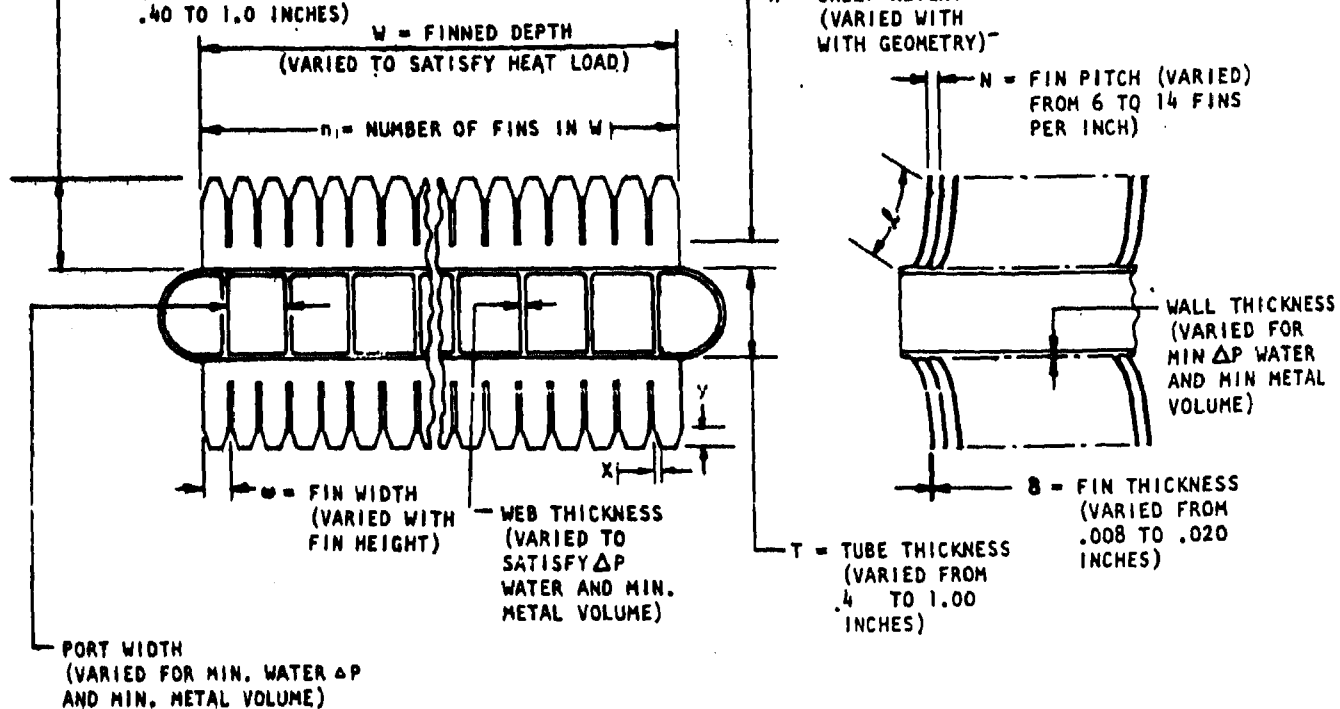
These investigations were based on assumed requirements for a reference 1000 MWe Nuclear power plant operating at two sites. One site is Middletown, U.S.A. which is based on meteorological conditions modeled on Boston, Massachusetts, and the other site is San Juan, New Mexico. Also, in an attempt to further evaluate the potential cost savings of the selected dry cooling system, a comparison was made with a conventional dry cooling system. This comparison was based on Total Evaluated Cost which is defined as the sum of the capital and penalty costs over the life of the plant.

In order to evaluate the economics of these improved dry cooling systems, a comparative evaluation was made with the results of a reference conventional dry cooling system. Table 1 provides a comparison of this dry cooling system with the selected dry cooling systems resulting from this study:

Comparative results obtained in this study for two versions of the dry cooling systems are summarized below in Table 2. Results are provided for both two-pass and one-pass cooling systems at the Middletown and San Juan sites for the conventional and selected cooling systems. These results show a substantial reduction in power consumption for the selected cooling system compared to the conventional cooling system for both sites and for both module lengths.

Table 2 also shows the Total Evaluated Cost which is the sum of the capital cost and the penalty cost associated with operating the cooling system over the life of the plant. The Total Evaluated Cost provides a convenient means of comparing, on a common basis, the total present value of the capital required to construct and operate various cooling

- (6) COO-4218-1 Conceptual Design and Cost Evaluation of a High Performance Dry Cooling System.



Similar Trane Concept

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- (6) COO-4218-1 Conceptual Design and Cost Evaluation of a High Performance Dry Cooling System.

<u>Cooling Cell Description</u>	<u>Conventional</u>	<u>Integral Fan Tube</u>	<u>1</u>
<u>Number of Water Passes</u>	<u>2</u>	<u>2</u>	<u>1</u>
Total Number of Dry Cooling Cells	338	169	156
Total Number of Fans	338	338	312
Diameter of Fans, Feet	28	28	30
Total Number of Cooling Modules	1,352	676	624
Number of Cooling Modules per Cell	4	4	4
Number of Fans per Cell	1	2	2
Design Air Inlet Temperature, °F	96	96	96
Design Water Inlet Temperature, °F	126	126	126
Design Cooling Range, °F	12	12	12
Total Fan and Pump Horsepower	63,520	31,740	35,400
<u>Cooling Module Description</u>			
Length of Cooling Module, Feet	53	80	80
Width of Cooling Module, Feet	10.5	12	12
Face Length of Cooling Module, Feet	52	79.25	79.25
Face Width of Cooling Module, Feet	10.15	11.75	11.75
Number of Fin-Tube Rows per Module	48 & 49	60	78
Number of Fin-Tubes Deep	4	2	1
Total Depth of Fin-Tubes, Inches	8.61	4.45	6.76
Tube Pitch, Inches	2.44	2.35	1.81
Number of Fins per Inch	10	10	11.5
Design Airflow per Module, (10) ⁶ Lb/Hr	1.46	2.125	2.425
Design Water Flow per Module, (10) ⁵ Lb/Hr	4.46	8.87	9.67

TABLE 2 COMPARISON OF SELECTED VS CONVENTIONAL DRY COOLING SYSTEM

Configuration	Reference			Selected		
	Conventional			Integral Fin-Tube		
Site Selection	Middletown		San Juan	Middletown		San Juan
ITD, °F	30	30	27	30	30	27
Water, Range, °F	12	12	12	12	12	12
Number of Water Passes	2	1	2	2	1	2
Module Length, Ft	53	80	53	80	80	80
Total Module Horsepower ⁽¹⁾	63,520	65,000	77,680	31,740	35,400	36,420
Total System Horsepower ⁽²⁾	88,320	88,270	102,140	53,970	57,700	62,170
Total Penalty Cost, \$(10) ⁶	72.0	71.8	81.1	53.9	55.4	59.7
Total Capital Cost, \$(10) ⁶	130.4	118.5	159.6	111.6	101.7	136.3
Total Evaluated Cost, \$(10) ⁶	202.4	190.3	240.7	165.5	157.1	196.0
			221.6			187.4

NOTES:

- (1) Total Fan Power plus Module Water Power Consumption
 (2) Total Fan Power plus Water Pumping Power (Modules & Piping)

systems. The capital costs represent the value of labor and hardware to construct a base plant cooling system. The penalty costs consists of a capacity and energy penalty to provide the makeup energy when the base plant cannot meet the demand load because of this base cooling system, a capacity and energy penalty to provide the power to operate the plant cooling system fans and pumps, and the maintenance costs of the cooling system.

Results summarized in Table 2 show a reduction in Total Evaluated Costs of 20% at Middletown and 26% at San Juan. The results in Table 2 also show that some improvement would occur in the conventional cooling system with single-pass 80 ft. by 12 ft. cooling modules. Comparing equal size single-pass cooling modules results in a reduction in Total Evaluated Costs of 15% at Middletown and 20% at San Juan with the selected cooling system employing the C-W Integral Fin-Tubes compared to the two-pass conventional cooling system.

As a point of interest the results obtained show a significant increase in the Total Evaluated Cost of the San Juan site compared to the Middletown site because of the meteorological differences between the two sites. These results are the product of extensive internal optimizations of the tower design which is beyond the scope of this paper. The full report⁽⁶⁾ should be consulted for this detail. Sensitivity evaluations, and re-design optimizations of the cooling modules using the C-W Integral Fin-Tubes were performed to evaluate the affect of ITD, fan operating conditions, escalation assumptions, fuel costs and hardware costs.

The substantial improvement predicted by the results of this study, in comparison to the reference dry cooling system, is due primarily to the higher heat transfer and lower pressure loss of the C-W Integral Fin-Tubes compared to round fin-tubes. Figure 2 illustrates this improvement. This figure compares a composite of performance for various C-W Integral Fin-Tube geometries vs. performance data for a composite of round fin-tube geometries. Both sets of data cover a wide range of fin and tube geometries and can be considered to be representative of their levels of performance. This data is presented in terms of the Colburn heat transfer coefficient, J , divided by the fin-tube friction factor, F . This ratio can be shown to be inversely proportional to power consumption at constant heat load and for constant site conditions.

It can be seen from Figure 2 that the general level of performance for integral fin-tubes is significantly higher than for conventional round fin-tubes. Also, it can be seen on this figure, that the general range of data assumed for this study is conservative, compared to the total range of data obtained with these integral fin-tubes during several years of experimental evaluations at C-W.

Figure 3 shows the arrangements of the tower.

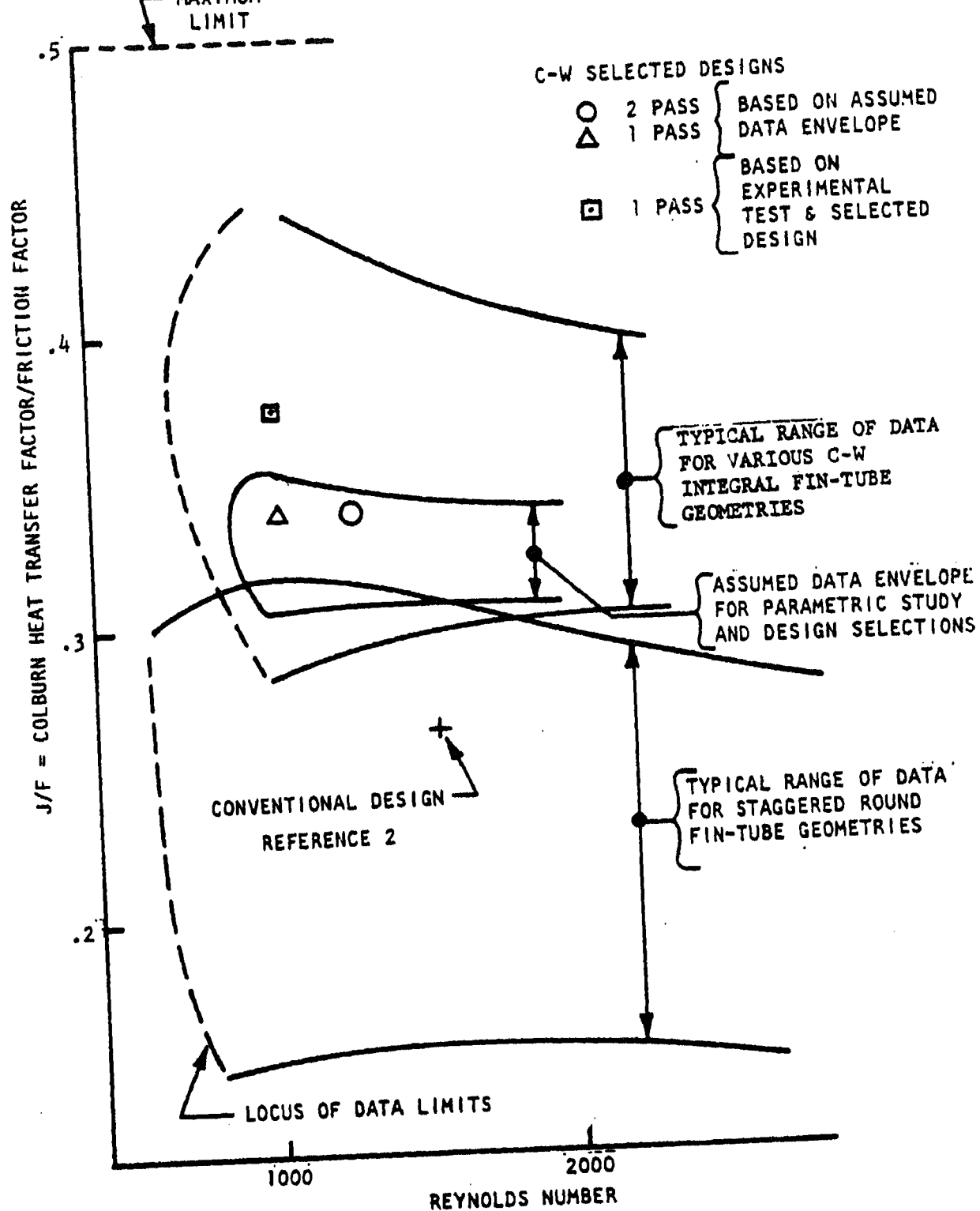
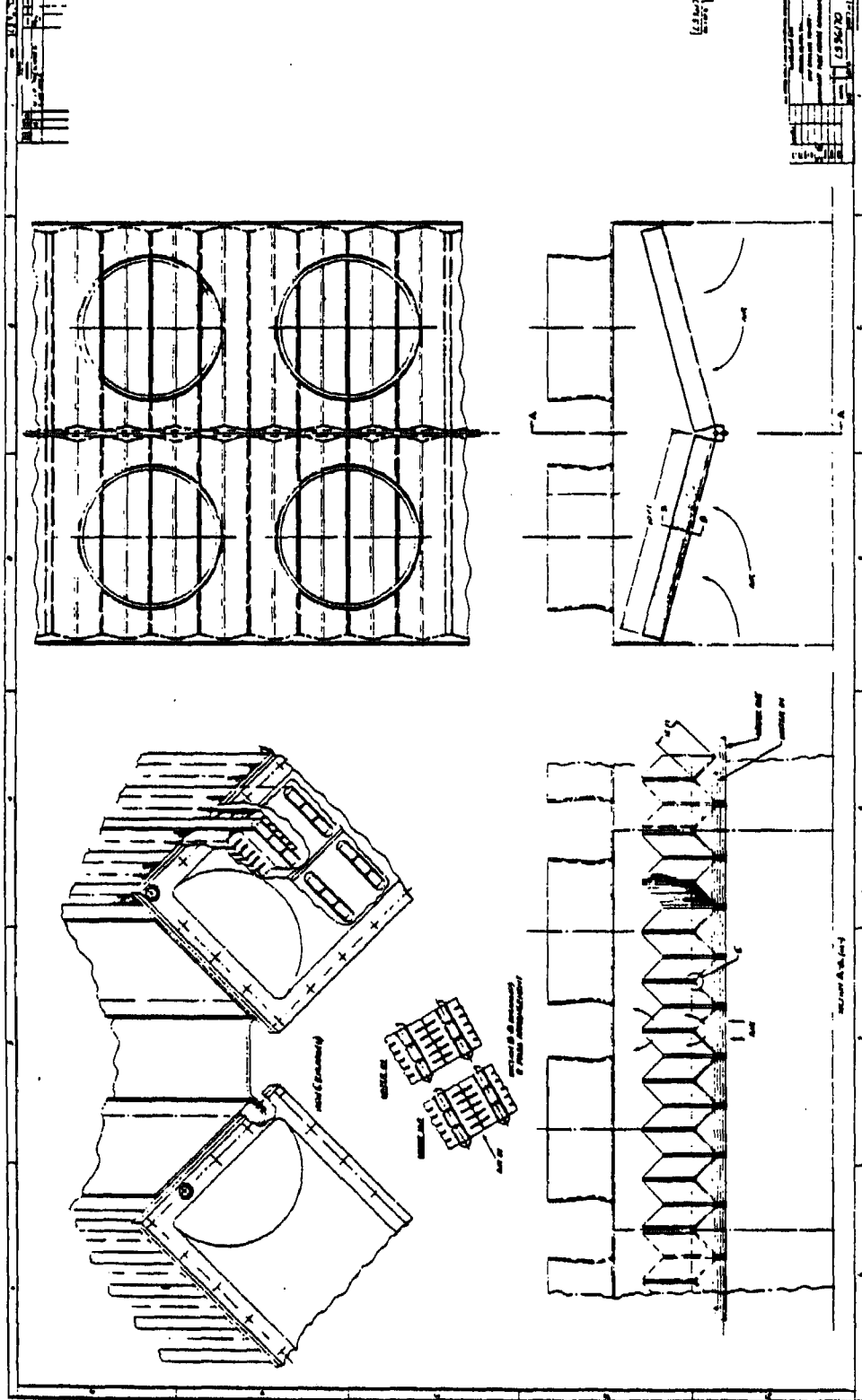


Figure 2



(C-W LAYOUT 1)
TWO-PASS DRY COOKING
USING C-W INTERLOCKING

Figure 3

2. HEDL* Power Plant Water Program

Principal Investigator: J. L. Sonnichsen, HEDL

The following discussion concerns the supporting work at HEDL on the water aspects of power plant heat dissipation. During the 1960's both the size and number of installed steam electric power plants increased considerably. Generally speaking both before and during this period, condenser cooling was accomplished by utilizing once-through cooling. This trend has caused considerable concern over the ability of our various water bodies to allow the required and projected water withdrawal rates, the associated evaporation rates and projected heat loads. Obviously with fewer and smaller units it was relatively easy earlier to find suitable sites for once-through cooling, however, the problem became much more acute as the size and number of thermal power plants began to increase. As a means of protecting our waterways, thermal pollution control standards emerged during the late 1960's and early 1970's. The combination of economy of scale, growing demand, and environmental protection has had a significant effect upon condenser cooling design. For example, in the mid-1960's once-through cooling systems accounted for over 90% of the added generation capacity, whereas today 20% or less of the added generation capacity is cooled by once-through cooling systems. As a first order of magnitude, evaporative cooling methods evaporate approximately twice the amount of water as when once-through cooling methods are used; although the withdrawal rate for once-through cooling is very much greater (30X) than for evaporative cooling. This withdrawal (of once-through) can be a problem for very large and multiple power plant sites and for streams with either low or highly variable water flow rates.

Unfortunately, in the long run, this change in trend to off-stream cooling appears to trade one type of problem for another. Whereas in the past primary concern centered on potential degradation of the water resource through thermal pollution, and damage to life forms passed through power plants with large once-through cooling systems, the current trend places an increased burden on the water resource in terms of evaporation. How successfully this trade-off can be accomplished is of course dependent upon the size of the resource in question and its various competing uses. In some water-scarce regions of this country the limit of water consumption has already been reached, and undoubtedly in future years water deficits will appear elsewhere. The use of large-scale evaporative cooling systems will obviously play a significant role in determining what areas are affected. In addition, new cooling concepts

*Hanford Engineering Development Laboratory of Westinghouse Electric Company, Hanford, Washington.

such as dry cooling and dry/wet cooling may have to be brought into play much sooner than currently realized.⁽⁷⁾

To meet the needs of various groups involved in planning for electrical power expansion in the face of the water problem a computerized water data system was initiated at HEDL. The system was designed primarily to assist these engaged in siting thermal power plants. By using the 2000 water resources cataloging units of the United States, the national water resource is indexed in a power plant data information retrieval system and the same water resource cataloging unit is used to index the power plant data which defines the water demand.

To model the demand for water within the thermal power plant sector of the U.S. economy, a simple input/output technique using normalized data on forecasted electrical energy growth is employed. Demand coefficients are multiplied by consumptive use or evaporative loss coefficients to obtain an effective consumptive use factor for each subregion, i.e., $(MWe) \cdot \frac{MWt}{MWe} \cdot \frac{cfs}{MWt}$ where MWe = electrical megawatts, MWt = thermal megawatts, and cfs = cubic feet per second.

The water resources element of the information system contains basically four types of data: data on the water resource cataloging unit, surface water data, ground water data, and data on oceans and bays. Table 3 provides a summary of the water data incorporated in the system. Comments on water rights are not presently included in the system but are planned to be added in the future. The intent of such a feature would be to provide a description of the overall status or allocation, if appropriated, etc., for water in each water resource cataloging unit.

The sources of the data in the system are reports published by various state and federal agencies in the United States. In addition to data on surface water an extensive effort has been placed upon collecting and organizing ground water data. Ground water is used extensively in some parts of the United States. At the present time ground water is being withdrawn at a rate of 80 billion gallons/day and as a point of interest twenty-five percent of the total withdrawal is in the state of California. In addition, some regions are withdrawing ground water at rates which probably cannot continue.

(7) HEDL-TME-76-82, "Assessment of Requirements for Dry Towers."

Table 3

WATER RESOURCE DATA

Data provided for each (8-digit) Water Resource Cataloging Unit

- Area Description
- o Approximate area - square miles
 - o State
 - o Dominant county
 - o Approximate current population
 - o Average, minimum and maximum run-off
 - o Water rights status (available 1980)
 - o Competing water use data (available 1980)
- Surface Water (River, Lakes and Reservoirs)
- o Rivers (4 maximum per cataloging unit)
 - Name
 - Average annual flow (cfs)
 - Monthly flow (by month for 50, 90, 95% probability)
 - Mean, maximum and minimum temperature
 - Total dissolved solids
 - Hardness
 - pH
 - o Lakes or reservoirs (4 maximum per cataloging unit)
 - Name
 - Area
 - Volume
 - Mean, maximum and minimum temperatures
 - Total dissolved solids
 - Hardness
 - pH
- Ground Water (maximum of 4 aquifers per cataloging unit)
- o Name
 - o Depth (below ground level)
 - o Thickness
 - o Total dissolved solids
 - o Hardness
 - o pH
 - o Temperature
 - o Specific capacity
 - o Yield of large diameter well
 - o Committed water rights (available 1980)
- Ocean/Bays (1 only per cataloging unit)
- o Name
 - o Salinity
 - o Mean, maximum and minimum temperature

Table 4

GENERATING PLANT DATA

Data provided for each thermal generating plant with 100 MWe or greater. Applicable data for hydroelectric are included for convenience.

General Plant Information

- o Plant name
- o Utility name
- o Plant location
 - City, county, state
 - Water resource cataloging unit
 - Latitude and longitude
 - Federal Energy Regulatory Commission power supply region
- o Plant type
- o Plant capacity (MWe)
- o First year of commercial operation

Plant Cooling Information

- o Type (once-through, tower, etc.)
- o Cooling water source
- o Flow rate of receiving water body
- o Withdrawal, consumption, blowdown, discharge rates

Plant Operational Data (yearly)

- o Generation
- o Heat rate
- o Capacity factor

The major problems associated with defining the ground water potential are due to: 1) the heterogenous nature of ground water supplies, and 2) identifying the existence and/or boundaries for each aquifer. To date the primary emphasis has been directed towards first defining, and second obtaining data on high yield aquifers. The primary source for ground water data is the U.S. Geological Survey WATSTORE ground water site Inventory File. In the ground water site Inventory File are data for more than 600,000 wells located in the United States.

Data on hydroelectric and thermal power plants with a capacity rating of 100 MWe or more are also included in the information system. Table 4 summarizes the data included for these systems.

For purposes of comparison it is worthwhile to note that in 1975 water withdrawals for steam-electric power plants were 90 billion gallons per day (3.79 million cubic meters per day) representing ninety-four percent of all withdrawals for energy production in the United States and twenty-six percent of the total fresh water withdrawals. With the trend towards off-stream cooling (e.g., use of cooling towers, ponds, etc.), the total withdrawal of surface waters for purposes of cooling thermal power plants are forecasted to decrease in the years ahead. However, consumptive use through blowdown and evaporation are forecasted to increase, since as mentioned earlier, once-through cooling results in less evaporation than evaporative cooling. It is in this connection that dry and dry/wet cooling becomes of paramount interest since those methods allow electrical power expansion without or with less water requirements.

General electrical generating plant data included in the system consists of plant name, utility name, plant location, plant type and overall rated capacity. The location of the plant is referenced with respect to: city, county, state, water resources cataloging unit, and latitude and longitude. Additional information on the specific Federal Energy Regulatory Commission power supply area and region served as well as the year of commercial start up are also included. Of particular importance is the inclusion of data on the type of cooling system. The source of the cooling water is also included in the information system. Yearly power plant operational data such as total generation, heat rate, and capacity factor are also included.

The data on power plants and water resources are organized into an hierarchical structure for purposes of retrieval. The information system is presently operational and provides either batch or on-line output modes.

Recognizing that a continuing need exists for updating projections on power growth, a predictive model has been developed for use in conjuncti

with the information system. As indicated in the introduction, supply and demand modules were developed using basic input-output techniques.

Information on existing and projected power growth and transmission facilities has been synthesized into 230 power generation areas as shown in Figure 4.

Normalized power growth coefficients were developed for each of the power generation areas based upon forecasted economic and agricultural growth characteristics prepared by research economists. The 230 power generation areas were next correlated with the Water Resources Subbasins. The 204 Water Resources Subbasins in the contiguous United States are shown in Figure 5. Each of the water resources subbasins contains on the average, 10 cataloging units. Using this approach, the total demand for electricity is inputted to the predictive model and the model is used to estimate the specific water demand in each water resource subbasin. Comparison can then be made regarding the water supply and demand for water or a subbasin, which can be extrapolated into water resource cataloging units. In the future, various programs of power plant growth scenarios can be developed and the variation of water requirements can be investigated on local regional and national levels.

The information system is operational and a number of inquiries for data have been received.

Additional development of the predictive capability are planned. A future model will relate supply and demand through the use of specific end use coefficients for each primary use of electrical energy; industrial, residential, and commercial. A demand model will be formulated for each Water Resource Subbasin. The demand for electrical energy in each Water Resource Subbasin can then be evaluated as a function of time, using economic activity factors and population as the primary independent variables. The electrical demand can then be compared with the proposed supply and water availability thus defining where advanced power plant cooling methods need to be used and enabling water use input analyses to be made for these cooling methods. This system is available for use by DOE activities and information on this can be obtained from J. C. Sonnichsen at HEDL.

3. Wind Effects Study at Cornell University

Principal Investigator: Dr. Frank Moore, Cornell University

It has been found that wind adversely affects the performance of cooling towers, especially natural draft dry cooling towers. These

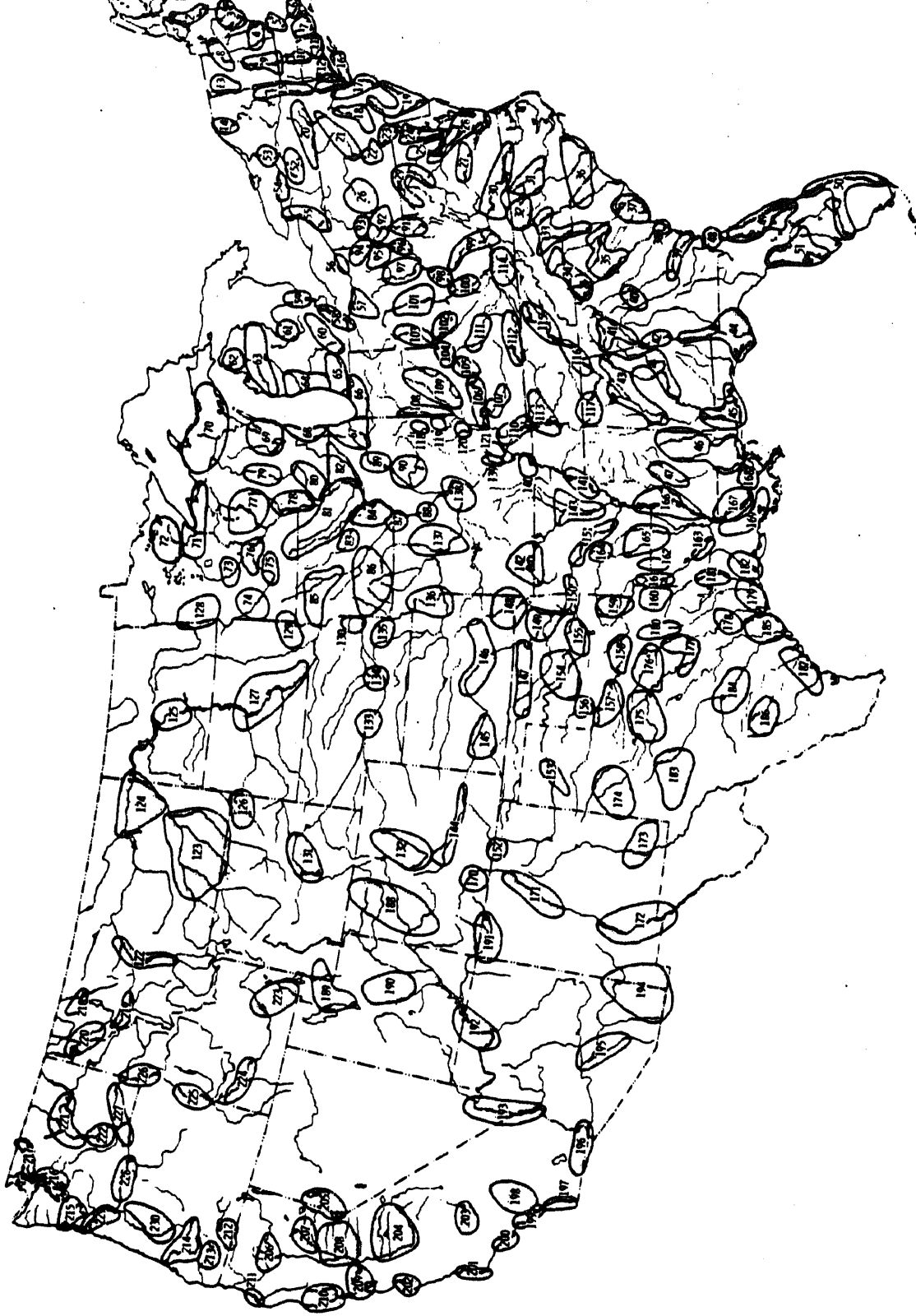
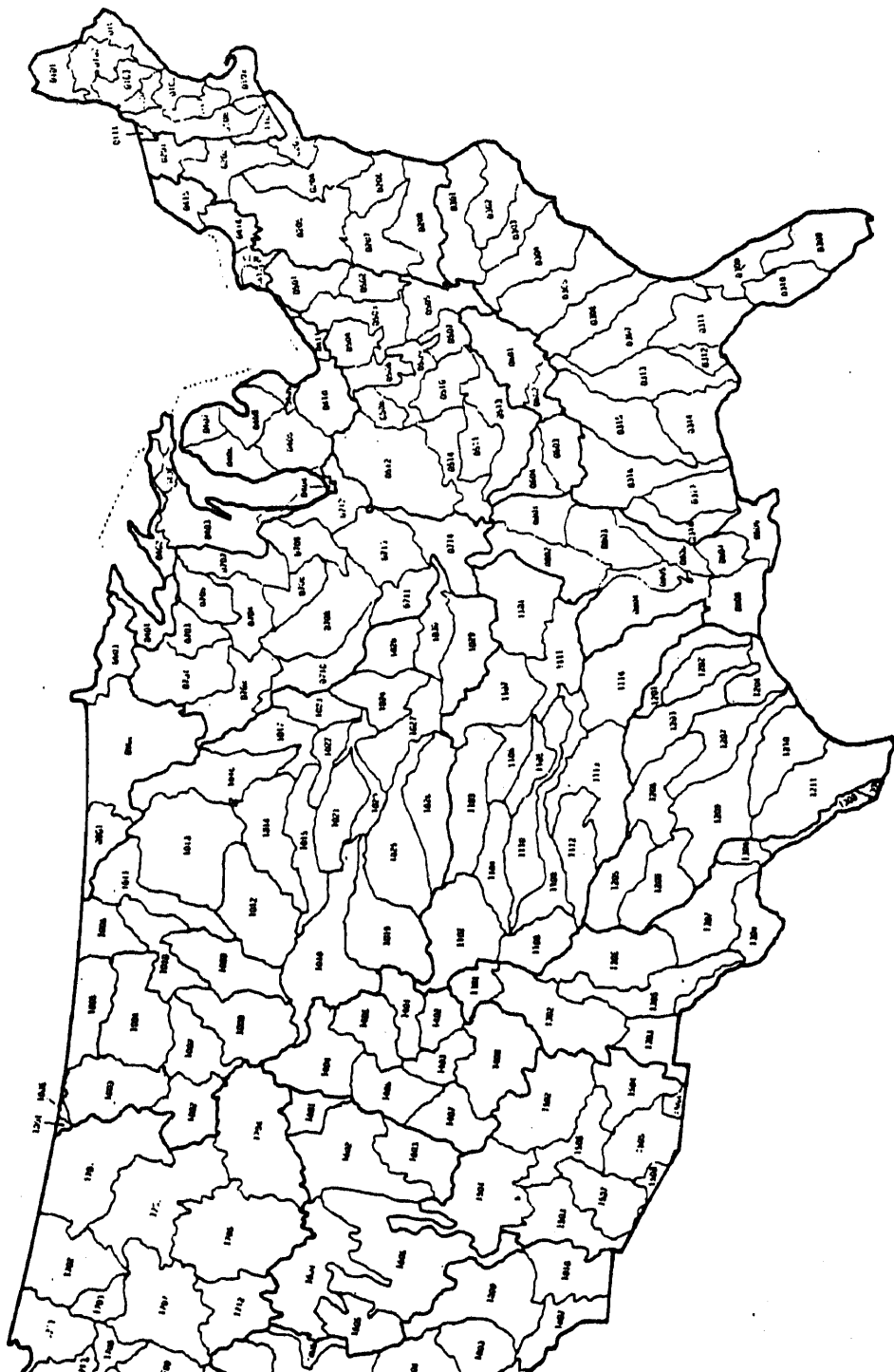


Figure 4 - Power Generation Areas in the United States



effects have not been thoroughly understood; therefore a university type effort has been supported in this area for several years. This effort is directed at obtaining a basic understanding of the various phenomena involved and thus hopefully to point the way toward designs which would be less affected by wind.

The wind effect is a phenomena which has been largely experienced in other countries inasmuch as only a few dry towers have been built here; although with increasing interest in dry cooling in this country the wind effect problems will become more important here in the future. Figure 6 shows the effects which have been found. The increase in condenser temperature indicated is sufficient to decrease primary power plant performance a significant amount, say up to about 10% for natural draft dry towers of present-day designs abroad.

Higher pressure loss heat exchangers such as these found in mechanical draft towers are less affected by wind but wind can cause effects due to circulation effects such as re-ingestion of tower effluent or from flow disturbance caused by adjacent structures. In order to better understand this area, a largely theoretical effect has been supported at Cornell University in related NSF and DOE programs. In general, the two programs have concentrated on separate parts of the wind effects work. NSF has concentrated on internal aerodynamics and DOE has largely concentrated on the external effects of tower design, topography, profiles, etc.

A comprehensive report⁽⁸⁾ of the work thus far accomplished has been issued. In the reported work it has been deduced that the basic approach to heat exchanger arrangement is the primary cause of the heat exchanger part of the loss. In order to conserve tower cost, heat exchanger height and/or tower base diameter, the heat exchange sections are arranged in accordian or folded fashion. Figure 7 illustrates two of the world's major large air cooled towers.

This folded arrangement of heat exchangers causes flow into the oblique heat exchanger section to be driven "into the corner," so to speak, at the windward front face of a tower and obliquely "around the corner" to the sides of the tower when the heat exchangers are arranged around the edge of the base as at Rugeley, or if the heat exchanger is placed under the tower as at Grootvlei, similar flow separations occur. These arrangements are illustrated in Figure 7 and Figure 8. These displacements

(8) COO-2924-1. Air Flow in Dry Natural Draft Cooling Towers Subject to Wind, in Cornell University, F. K. Moore, K. E. Torrence.

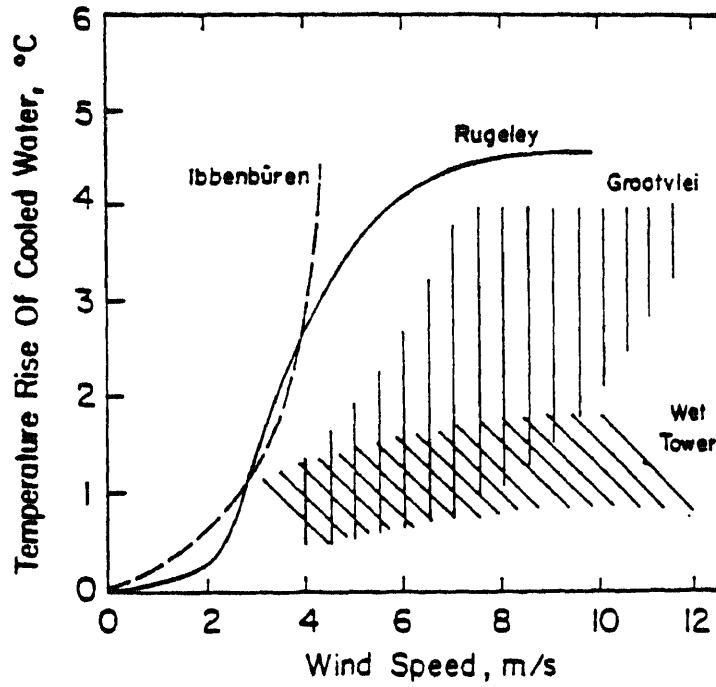
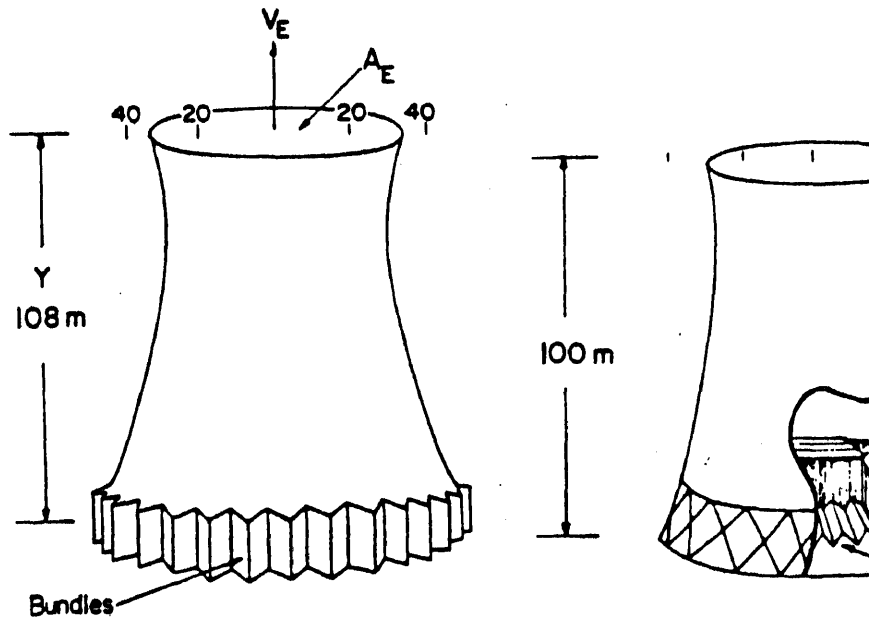
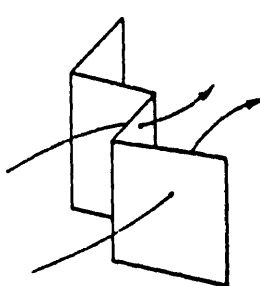
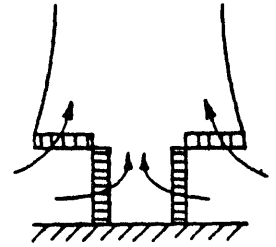
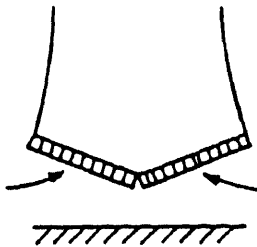
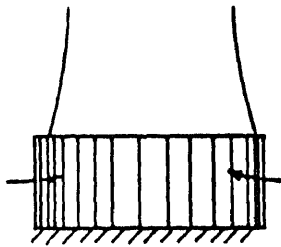
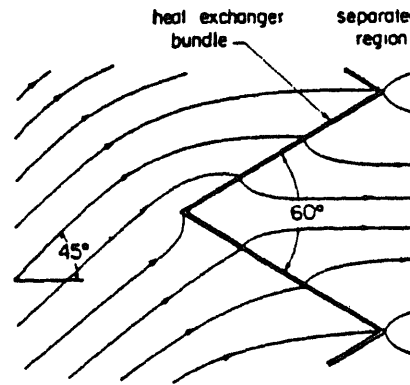
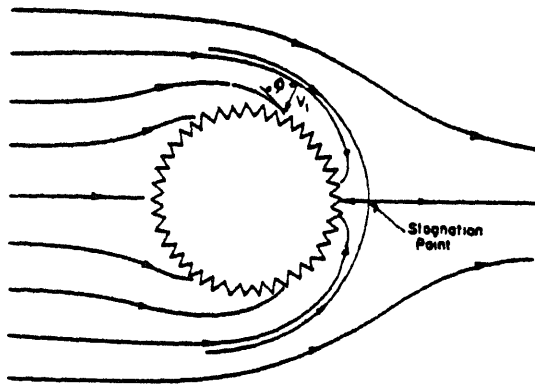


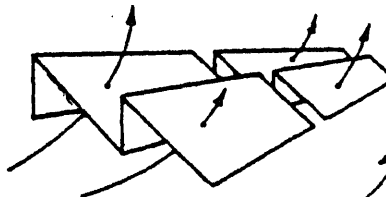
Figure 7 EXISTING COOLING TOWER FOR WHICH WIND EFFECTS DATA IS AVAILABLE



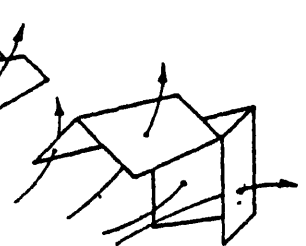
HEAT EXCHANGER ARRANGEMENTS



"Cylindrical"



"Radial II"



"Top Hat II"



"

flows result in reduced effective frontal area for flow and thus reduce the basic heat transfer.

In addition, there are wind effects which can affect the performance at the tower at the top since the wind causes the exit to be effectively smaller diameter, due to flow separation at the windward side, thus increasing the exit loss. Figure 9 illustrates this effect. Also, analysis has shown that atmospheric temperature inversion can set up a condition where upper warmer air is drawn into the tower base resulting in reduced cooling. These various effects have been explored both by analysis and by observation of existing towers abroad.

Based on these investigations, the Cornell workers have decided that aerodynamic performance of heat exchangers can be "improved" if the designs are such as to turn the flow smoothly into the heat exchanger bundles and by providing a uniform well-mixed flow as the flow approaches the tower exit. Several ways of doing these things are illustrated in Figure 10. In the current year's program some wind tunnel model work will be undertaken on potential tower design improvements along these lines.

Cornell has an interest in investigating ways of reducing tower height (which would ordinarily be adverse for wind effects) because the height of and the visual appearance of natural draft towers is a definite problem area. Dr. Moore has in mind working out a low natural draft tower design which would be less affected than normally by the wind. The NSF effort in the coming year will be on oblique flow into heat exchangers.

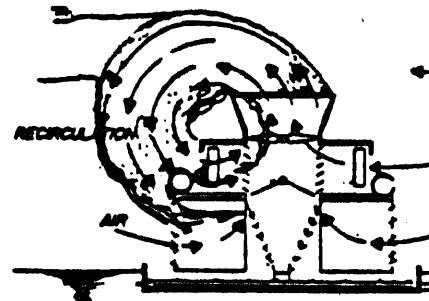
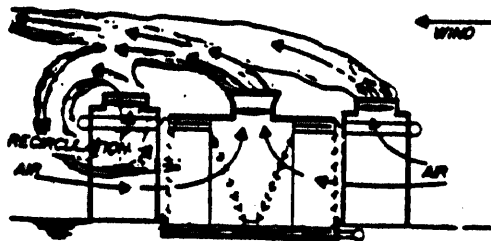
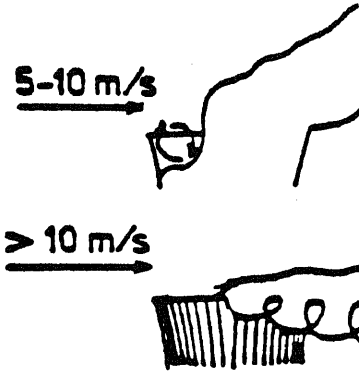
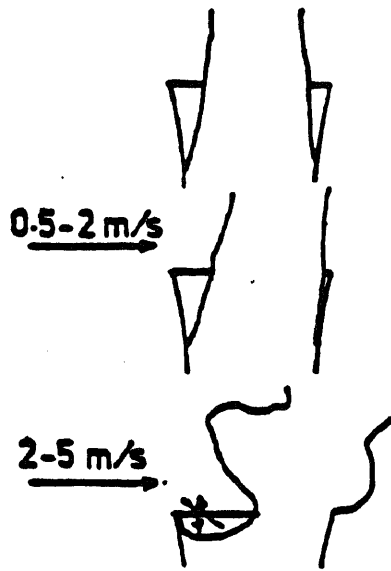
This program is also of interest for cooling towers other than dry towers but to lesser degree. Of course, an effect of as little as 1% is important to electrical generating plants.

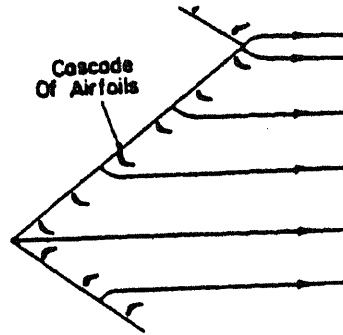
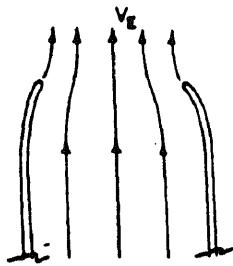
These three efforts reported in this paper are peripheral or supporting studies but all three are useful in the power plant heat dissipation on a broad basis in addition to supporting the EPRI/EPA/DOE dry/wet cooling tower technology program now going on at Battelle PNL.

Additional references on the Cornell program:

- (9) "Effects of Aerodynamic Losses on the Performance of Large Dry Cooling Towers," submitted to ASME (WAM). F. K. Moore.
- (10) "Aerodynamics of the Heat-Exchangers and Their Arrangement in Large Dry Cooling Towers," to ASME (WAM). F. K. Moore.
- (11) MS Thesis (Girolami) "A Numerical Study of Entrance Flow Losses in Zig-Zag Arrays of High-Drag Heat Exchangers." F. M. Girolami.
- (12) "Turbulent Flow and Pressure Losses Behind Oblique High-Drag Heat Exchangers." F. K. Moore, L. P. Bisterelli, Jr.

ILLUSTRATED WIND EFFECTS





(a) Downstream Cascade

(b) Cylinder A

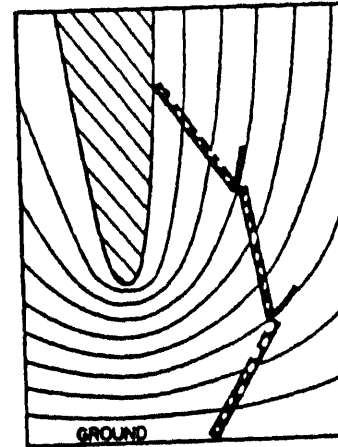
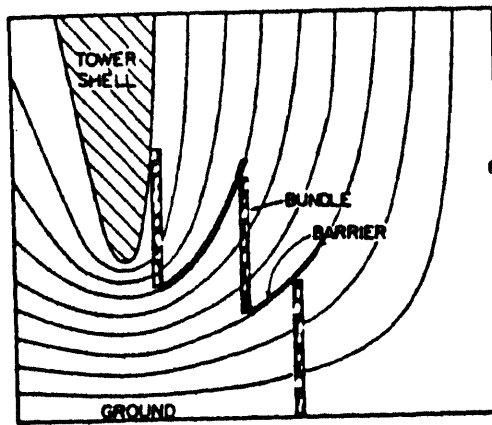


Figure 10

USE OF WASTE HEAT FROM NUCLEAR POWER PLANTS

Mitchell Olszewski
Oak Ridge National Laboratory

ABSTRACT

This paper details the Department of Energy (DOE) program concerning utilization of power plant reject heat conducted by the Oak Ridge National Laboratory (ORNL). A brief description of the historical development of the program is given and results of recent studies are outlined to indicate the scope of present efforts. A description of a DOE-sponsored project assessing uses for reject heat from the Vermont Yankee Nuclear Station is also given.

INTRODUCTION

It has been recognized that, because of power cycle operating conditions, nuclear power plants reject more waste heat per unit of electricity produced than comparable fossil stations. Because the reject heat dissipation problem is more severe for nuclear stations, the Advanced Systems and Materials Production Division of DOE (formerly Advanced Concepts Evaluation Branch - Nuclear Research and Applications Division) has sponsored a Beneficial Uses of Waste Heat Program at the Oak Ridge National Laboratory (ORNL) for a number of years. This program has consisted primarily of assessment and analysis tasks although cooperative efforts have been established with utilities for demonstrations of waste heat utilization concepts.

This effort is limited to consideration of the normally occurring power plant waste or reject heat which results from the use of conventional cooling methods (i.e., generally 49°C or less). This temperature regime would be most logically used for growing plants or animals. DOE has other programs such as cogeneration and district heat which use bleed steam at higher temperature. These efforts are described in other papers.

This paper traces the ORNL program in low temperature waste heat utilization from its inception to the present. Results of recent studies are outlined to indicate the scope of present efforts.

This paper also describes a small DOE sponsored study examining uses for reject heat from the Vermont Yankee Nuclear Station. This study was performed by the Vermont Yankee Nuclear Power Corporation and concentrated on aquaculture possibilities.

HISTORICAL DEVELOPMENT OF THE ORNL PROGRAM

The system examined for heating and cooling greenhouses and animal shelters is illustrated in Fig. 1. It involves the use of a conventional pad and fan system with finned-tube coils mounted downstream of the pads. The pads are typically filled with a fibrous material. Condenser cooling water drips vertically down along the fibers while air flows horizontally through the pad. The air is heated or cooled depending on the ratio of sensible to latent heat transfer. The cooled water is collected at the bottom of the pad and returned to the condenser.

Warm water from the condenser can also be pumped through the finned-tube coils. The air coming from the pads is heated and dried by the addition of sensible heat from the fins. By varying the relative fractions of water pumped through the pads and coils and the airflow rate, the temperature and humidity of the air entering the greenhouse or animal shelter can be adjusted. This system can be used for summer cooling and winter heating. Heated or cooled air can be allowed to pass through the house and out the other end through exhaust fans. Under certain environmental conditions, such as cold weather, automatically controlled louvers would permit recirculation of the air through the attic.

Further analytical studies [8] considered aquacultural uses of waste heat. This study concentrated on shrimp production using waste heat to enhance growth. The primary emphasis of the program, however, continued to be greenhouse applications.

These feasibility studies led to experimental greenhouse efforts [3] and sponsorship of waste heat workshops in Oak Ridge in 1970 and Gatlinburg, Tennessee in 1971 [9]. The experimental greenhouse efforts were conducted in a small 6.1×14.6 m (20×48 ft) Mylar greenhouse constructed at ORNL. The aspen fiber pads were fed with 40°C (105°F) water at a rate of 37.2 l/m (3 gpm/ft) of pad length from an air conditioning cooling tower. The greenhouse was operated from the fall of 1970 to the summer of 1971 to determine the operating characteristics of the pad and finned-tube coil system in the heating and cooling mode.

The ORNL experimental greenhouse efforts led to a joint greenhouse program with the Tennessee Valley Authority (TVA). This program resulted in the construction and operation of a pilot greenhouse for waste heat research which is located at the TVA facilities in Muscle Shoals, Alabama. The greenhouse, shown schematically in Fig. 1, is a conventional aluminum-framed glass-glazed structure. An electric boiler is used to simulate the discharge from a power plant condenser.

Aspen pads were initially used as the evaporative pad material. However, experimental work performed at ORNL [10] demonstrated that CELdek,* a cooling tower packing was a superior heat and mass transfer media. The aspen pads were replaced by CELdek in 1975 prior to planting the fall crop.

CURRENT ORNL PROGRAM

The current ORNL waste heat utilization program is primarily concerned with support for the Browns Ferry demonstration greenhouse and economic and technical assessments of waste heat utilization technologies. Support of the Browns Ferry project has thus far led ORNL to assume responsibility for the greenhouse design. This design was done by the Environmental Research Laboratory of the University of Arizona, under contract to ORNL. Construction of the greenhouse, based on the DOE-supplied design, has been completed and the initial greenhouse crop has been planted. Present and future support of this effort will include technical support and experimental verification, at ORNL, of any unique features of the greenhouse design.

The technical and economic assessment facet of the program has led to investigations of economic aspects of waste heat use in greenhouses, new aquaculture systems to utilize waste heat, overall assessments of waste heat utilization technologies, utilization of waste heat from gaseous diffusion plants, and plastic heat exchanger investigations. The effort to utilize gaseous diffusion plant waste heat has primarily involved technical support for various groups interested in the concept. Information concerning the amount of heat and temperature levels available for on- and off-site use has been obtained for the three DOE Gaseous Diffusion Plants at Portsmouth, Ohio, Paducah, Kentucky, and Oak Ridge, Tennessee. Details of the cooling water piping system have also been obtained and possible tapping points (to take the cooling water to heat exchanger for off-site use of the heat) have been identified. This information was obtained at DOE's request and forwarded to the DOE committee examining this question. An analysis of the overall technical and economic aspect of using gaseous diffusion plant waste heat was also prepared by ORNL.

An analysis [13] was performed by ORNL to determine the economic feasibility of heating greenhouses with power plant reject heat. The recently updated [results indicate that for a 2.5 ha (10 acre) greenhouse located within 305 m (1000 ft) of the power station, waste heat is the economic choice, when compared to fossil fuels at \$1.66-\$2.37/GJ (\$1.75-\$2.50/10⁶ Btu), for greenhouse winter heating if the condenser cooling water outlet temperature is 27°C (80°F) or above. If the condenser outlet temperature drops to 21°C (70°F), the economic feasibility of using waste heat depends upon climate and the cost of fossil fuels. For condenser outlet temperatures below 21°C (70°F) the waste heat system is not economically feasible.

These results are based on a greenhouse design similar to that illustrated in Fig. 1. For the purposes of this study the finned tube exchanger was not included in the heating system design.

Examination of typical U.S. greenhouse fixed and operating costs and revenue for production of two tomato crops per year, indicated that the use of fossil fuels resulted in an operating loss for all but mild climates. As illustrated in Fig. 2, use of waste heat with 27°C (80°F) water results in an operating

house heating depended upon the available greenhouse cooling water outlet temperature. Therefore, any decision concerning the feasibility of waste heat use for greenhouses should include consideration of the power plant design.

Drawing on the biological expertise of ORNL's Environmental Sciences Division, studies [15,16] were performed to assess the potential use of waste heat in aquaculture using a polyculture concept. After surveying current aquaculture efforts in the United States, it became evident that the major portion of work concentrates on intensive culture of species such as lobster, shrimp, trout, salmon and catfish. The high cost of these species, arising partly from the need for expensive, high protein feed (typically 30 to 40% of operating costs are due to feed costs), limits their market and, therefore, the potential for waste heat utilization.

These studies evaluated an aquaculture system using extensive culture techniques and natural ecosystem food supplies. Fin and shellfish that feed on lower trophic levels of the food chain were utilized in the system. Addition of waste heat was used to provide regulated growth temperatures for phytoplankton and zooplankton cultures and for the fish systems. Planktonic growth is further enhanced by the addition of nutrients available from a variety of waste streams.

The planktonic biomass is used as the food source for fish culture and polyculture techniques are employed to utilize all feeding niches in the ponds.

The species selection concentrated on fresh-water varieties because the majority of power plants, especially nuclear plants, are located inland. The preliminary study [15] concentrated on tilapia and carp arrays. However, it appears that tilapia have the greater potential for near term consumer acceptance. Therefore, a later, more detailed study [16] concentrated on tilapia. It should be noted, however, that suitable species (such as striped mullet, croaker, tarpon and sheepshead) are available for coastal sites.

The general design features of the system are illustrated in Fig. 3. Conceptually, the system functions in the following manner. A nutrient stream heated using power plant waste heat and flows into Pond I with an appropriate amount of diluent. Algae begin the uptake of nutrients, in Pond I, and are grazed upon by zooplankton. The overflow from Pond I, laden with algae and zooplankton, flows into Pond II where fish are grown. In Pond II fish consume algae, zooplankton, aquatic macrophytes (grown in the pond mud bottom) and benthic organisms. Water flows into Pond III laden with fish waste products and algae are again used to remove the nutrients. In Pond IV clams are used as living biofilters, straining algae and bacteria out of the water. Crayfish are used in Pond IV to consume the clam wastes. Protein production is, therefore, concentrated in fish, clams, and crayfish. A final "cleaning" pond containing aquatic vegetation may be necessary to produce a clean effluent.

Economic analysis of the system indicated that the system appears to be feasible. The projected production costs are shown in Figs. 4 and 5 for fixed charge rates of 15 and 25% respectively. As shown in the figures, these are a function of the fish production rate and pond operating costs.

attained at production levels less than 56,750 kg/ha-year (50,000 lb/acre-year). These criteria were supported by recent information concerning live-weight, pond-bank prices for tilapia [17] and fish production data [18]. From Fig. 4 it appears that at the expected production rate of 56,750 kg/ha-year (50,000 lb/acre-year) the production costs are below the target cost of \$1.32/kg (60¢/lb) when the capital charges are annualized using a 15% FCR. As shown in Fig. 5 the system is no longer feasible if a 3-hr aeration turnover time is used when the FCR is increased to 25%. The system does, however, remain feasible if a 12-hr turnover time is used.

Preliminary analysis of the clam production system indicated that the system was economically feasible if the clams could be sold for \$1.34/kg of clam meat (\$4.38/bu) which is about one-fourth the current price for clams.

These studies have concluded that the waste-heat aquaculture system appears to be a feasible option. However, experimental work is needed to verify system productivity assumptions.

In an effort to assess the implementation potential of waste heat utilization systems in the power industry, two related studies were performed. One study [19] examined the economic and marketing issues while the other [20] examined the question of land available for waste heat facilities around power stations.

The study pertaining to economic and marketing factors compared the primary heat utilization technologies in an effort to determine which have the greatest potential for wide-scale implementation in the power industry. The systems analyzed in this report included: (1) glass glazed greenhouses producing one crop per year, (2) undersoil heating, (3) algal ponds, (4) extensive pond aquaculture, (5) intensive raceway aquaculture and (6) animal shelters. Intensive aquaculture was used to indicate systems that use concrete raceways, high protein feeds and oxygenation systems in an effort to achieve the maximum yield from a body of water. Extensive systems are those that utilize natural ecosystem food chains and maximize growth by controlling water temperature.

The algal and aquaculture systems included both open and closed system operation. Open systems are those that use the condenser cooling water directly in the heat utilization system. Closed systems employ a heat exchanger to separate the two streams.

The systems were designed to accommodate, if possible, the yearly cooling needs of a 1000 MW(e) power plant. Based on the complex sizes, annual costs were estimated for these systems. These heat utilization system annual costs included only those costs directly associated with the heat utilization system. This includes capital items (greenhouses, raceways, etc.), land acquisition [if the system land requirements exceed the normal utility land area purchase of about 125 ha (500 acres)], and power costs associated with operation of the complex as a heat dissipation system.

Costs for circulating the condenser effluent through the heat utilization complex were calculated separately. This water

distribution cost was estimated assuming a square layout for the complex and use of prefabricated steel pipe conduit.

Several systems (i.e., greenhouses and animal shelters) are not capable of using the waste heat in summer and cooling towers must be constructed to accommodate this load. These costs were included as additional cooling system costs.

Based on these unit annual costs, products were selected for the heat utilization systems. Given the product selections, the projected unit annual revenue was computed for each system.

Using the annual revenue and cost estimates, an economic index was computed to compare the economic potential of the systems. The economic index used was the ratio of unit annual revenue and the unit annual cooling cost (the sum of the heat utilization system cost and, if required, the additional cooling system cost). This index was used to determine which systems would be economically attractive if constructed for use as a power plant cooling system.

The economic index results are presented in Fig. 6. It should be noted that site specific conditions, alternate economic assumptions or alternate system designs could alter the economic results. Use of plastic rather than glass greenhouses would reduce the capital costs by about 40%, but would result in higher operating costs because the house would need recovering every year or two. Likewise, plastic lined earthen raceways could be used in place of concrete raceways for intensive aquaculture. This would result in a 50% reduction in capital costs but would increase operating costs associated with cleaning the settling basin required in such systems.

A heat utilization index was similarly used to determine if product market constraints would restrict wide-scale use of the system. Based on the product selections, the area required to satisfy 100% of the U.S. demand for the system products was computed. The implementation merit index, presented in Fig. 7, was computed by dividing the area required to satisfy 100% of the U.S. demand by the area required to satisfy the heat dissipation needs of a 1000 MW(e) power plant. This index, therefore, indicates the number of 1000 MW(e) power plants required to satisfy the total U.S. demand for products from the heat utilization system. Essentially it is an indicator of the potential impact the system could have in the power generating industry.

Based on the economic and implementation indices, from Figs. 6 and 7, the technologies were ranked to indicate which showed the greatest potential for wide-scale use in the power generating industry. A summary of these rankings is presented in Table I. The three top ranked technologies (extensive pond aquaculture, animal shelters and algal ponds) all showed an economic index greater than one and a high implementation index. The other technologies usually ranked poorly in at least one of the indices.

The results of this assessment indicated that substantial implementation of waste heat could take place based on economic and marketing factors. From Fig. 7 it appears that reject heat from about 175,000 MW(e) of generating

TABLE I. RANKING OF WASTE HEAT
UTILIZATION TECHNOLOGIES

Ranking	System
1	Extensive pond aquaculture
2	Animal shelters
3	Algal ponds
4	Intensive raceway aquaculture
5	Undersoil heating
6	Greenhouses

These results suggested that power plant site information should be examined to determine if power plant land availability would permit waste heat implementation at the levels indicated by the economic and marketing assessment. The land availability assessment [20] concentrated on nuclear sites because information is readily available from the Preliminary Safety Analysis Reports that have been filed. The assessment was performed by defining a waste heat utilization factor for each operating and planned nuclear station. This factor is the percentage of the station's reject heat that could be utilized on the land available for such use at the site.

The results indicate that reject heat from 115,000 MW(e) of generating capacity could be utilized on the land which is available. The results further indicate that about half of this potential implementation is at stations that have enough land to accommodate waste heat utilization systems sized to use all of the reject heat of the station. Utilization of the remaining 50% is about equally distributed among sites capable of using between 10 and 90% of their reject heat. Further, it seems reasonable that for many applications an integrated waste heat complex, using several waste heat technologies, will be required to avoid marketing problems. It also appears that single application systems will be important for the sites that can use only a small fraction of their total reject heat.

A preliminary estimate of implementation at fossil stations indicated a potential about equal to that for the nuclear stations. Based on these estimates, it appears that implementation of waste heat utilization systems in the power industry will be limited by economic and marketing constraints rather than power plant land availability considerations.

Based on assessments of greenhouse and aquaculture applications, it has become clear that less expensive heat exchangers are required to transfer heat from the condenser cooling water to the waste-heat user. Experimental efforts have recently begun at ORNL to analyze and evaluate the use of plastic double-wall plates for heat exchanger applications. This concept would have the condenser water flow inside the panel while greenhouse air or aquaculture water flows over the exterior of the panel in a cross-flow configuration. The panels are commercially available in a number of materials including polypropylene and polycarbonate. Preliminary estimates indicate that although heat transfer

study are reported in Ref. 21, which can be obtained from Mr. E. P. Gaines, Jr. of the Vermont Yankee Nuclear Power Corporation. The aquaculture portion of the study was jointly supported by DOE. A corollary study concerning horticultural applications was sponsored by the Environmental Protection Agency (EPA) and will be detailed in a forthcoming EPA report. Since the two projects were interdependent by virtue of mutual support facilities (piping, pumps, service buildings, etc.), the two projects were combined into an integrated system concept which is described in this paper.

The primary objectives of the study were to examine and identify Vermont Yankee operating and environmental conditions that could affect the success of commercial aquaculture and horticulture enterprises utilizing condenser discharge water. In pursuing these objectives, plant and animal species having good potential for commercial aquaculture and horticulture were selected, a system concept integrating both horticulture and aquaculture endeavors with the necessary supporting facilities was developed and analyzed, and the impact of the 1958 Delaney Amendment to the U.S. Food, Drug, and Cosmetics Act was investigated. Reference 21 provides a discussion of the requirements of present laws and regulations as affecting on-site production of food items. A fundamental issue is whether a heat exchanger is a necessity to keep out radioactivity and biocidal material.

As developed in the study, the waste heat concept included three major components: the aquaculture facilities, the horticulture facilities and the mutual system support facilities (pumps, heat exchangers, control systems, etc). Figure 8 is a simplified sketch of these three components.

The aquaculture component includes a commercial fish-rearing facility consisting of eight enclosed raceways each 12 ft wide by 80 ft long. The facility is designed for the annual production of about 45,400 kg (100,000 lb) of live brook trout. The fish would be stocked in early October at 1 cm (4 in.) in length to be reared at a constant 13°C (55°F) until June of the following year when they will be harvested at a length of about 2.3 cm (9 in.).

Besides the commercial trout aquaculture facility, the aquaculture system component includes construction and long-term operation of a research facility dedicated to resolution of fundamental problems of intensive, closed-cycle fish farming. The design includes 9 circular rearing tanks each with 23 m² (250 ft²) of surface area and 8 smaller tanks providing a research area for 1000 fish.

Water supplied to these tanks will be in continuous circular motion and maintained at a temperature of about 16°C (60°F). The initial task of this facility is to produce approximately 25,000 Atlantic salmon from fingerling size to smolt size between the months of September and April of the following year. This would be in support of efforts to restore Atlantic salmon to the Connecticut River. The long range purpose of the laboratory, however, would be to generally address problems associated with intensive closed-cycle aquaculture.

The horticulture component consists of four specially designed greenhouses.

envisioned. Because of low water temperatures in the Vermont area and therefore relatively low condenser coolant effluent temperatures, supplemental heating sources were investigated.

A unique feature of the horticulture component is incorporation of an anaerobic digester, converting manure from an adjacent 220 animal dairy farm to biogas and concentrated fertilizer. Calculations indicate that sufficient manure is available from this source to adequately heat one of the experimental greenhouses solely by burning biogas in conventional gas heaters. The digester itself would be enhanced by the use of Vermont Yankee condenser effluent to pre-heat the manure slurry. Theoretical results indicate that this method could increase gas production by 40% or more during winter months.

This effort essentially represented completion of the conceptual design phase and no follow on work is planned by DOE. Any future development, implementing the study recommendations, would be on a commercial basis. The overall results of the Vermont study indicate that it is difficult to use waste heat in such a cold region when using once-through cooling in the winter time. This in no way changes the favorable outlook for waste heat use in general, especially where cooling towers are being used on a year-round basis.

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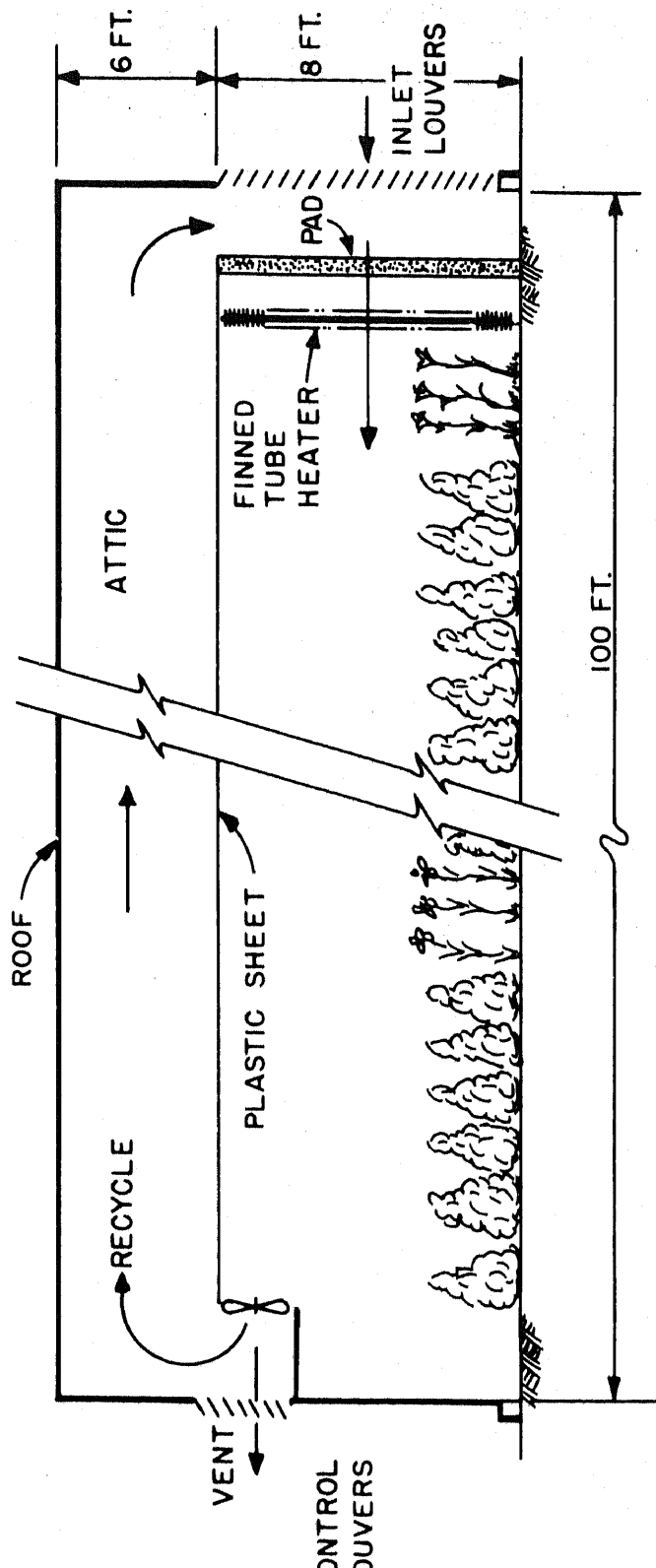


Fig. 1. Schematic of greenhouse or animal shelter heating system.

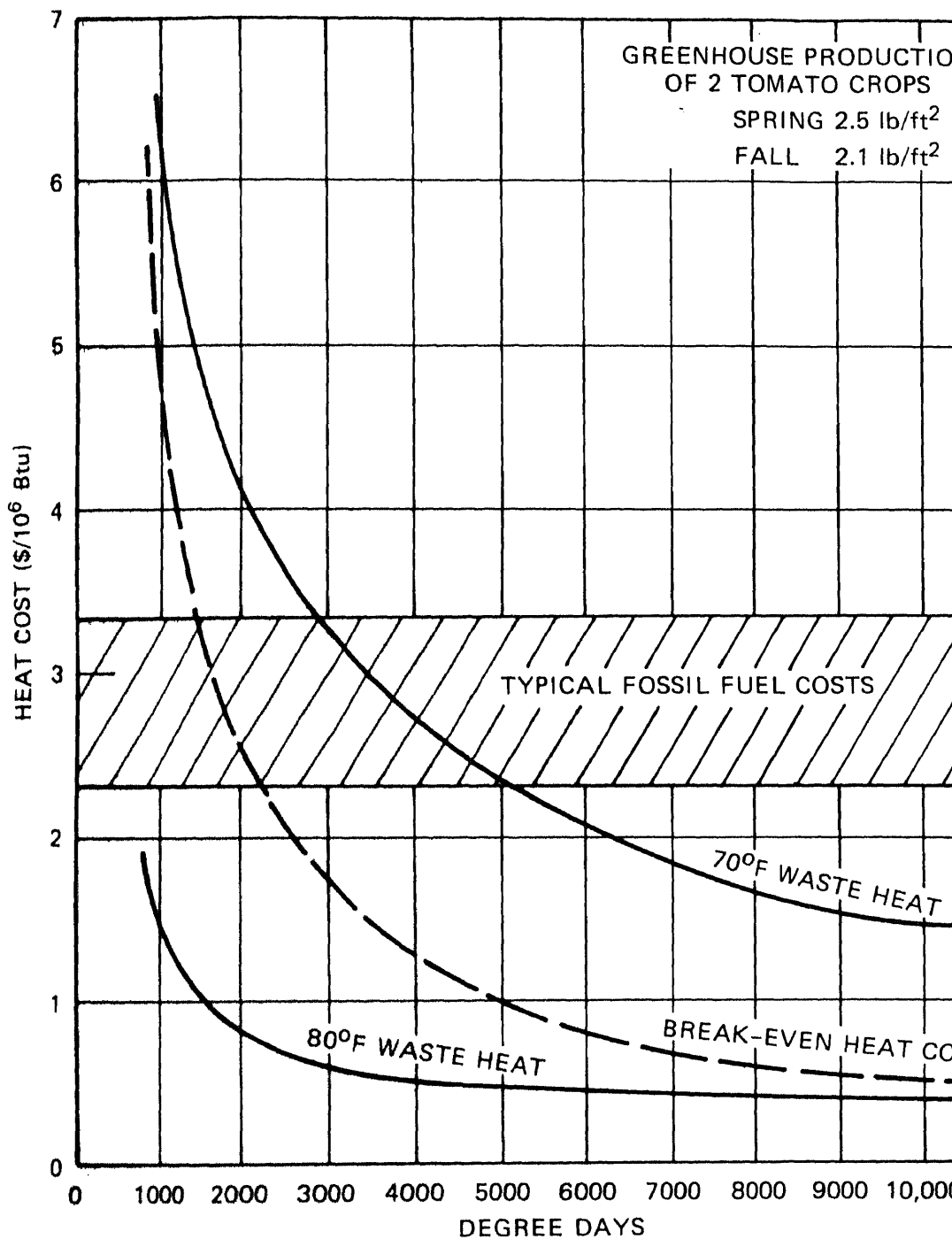


Fig. 2. Maximum heat cost for greenhouse break-even operation

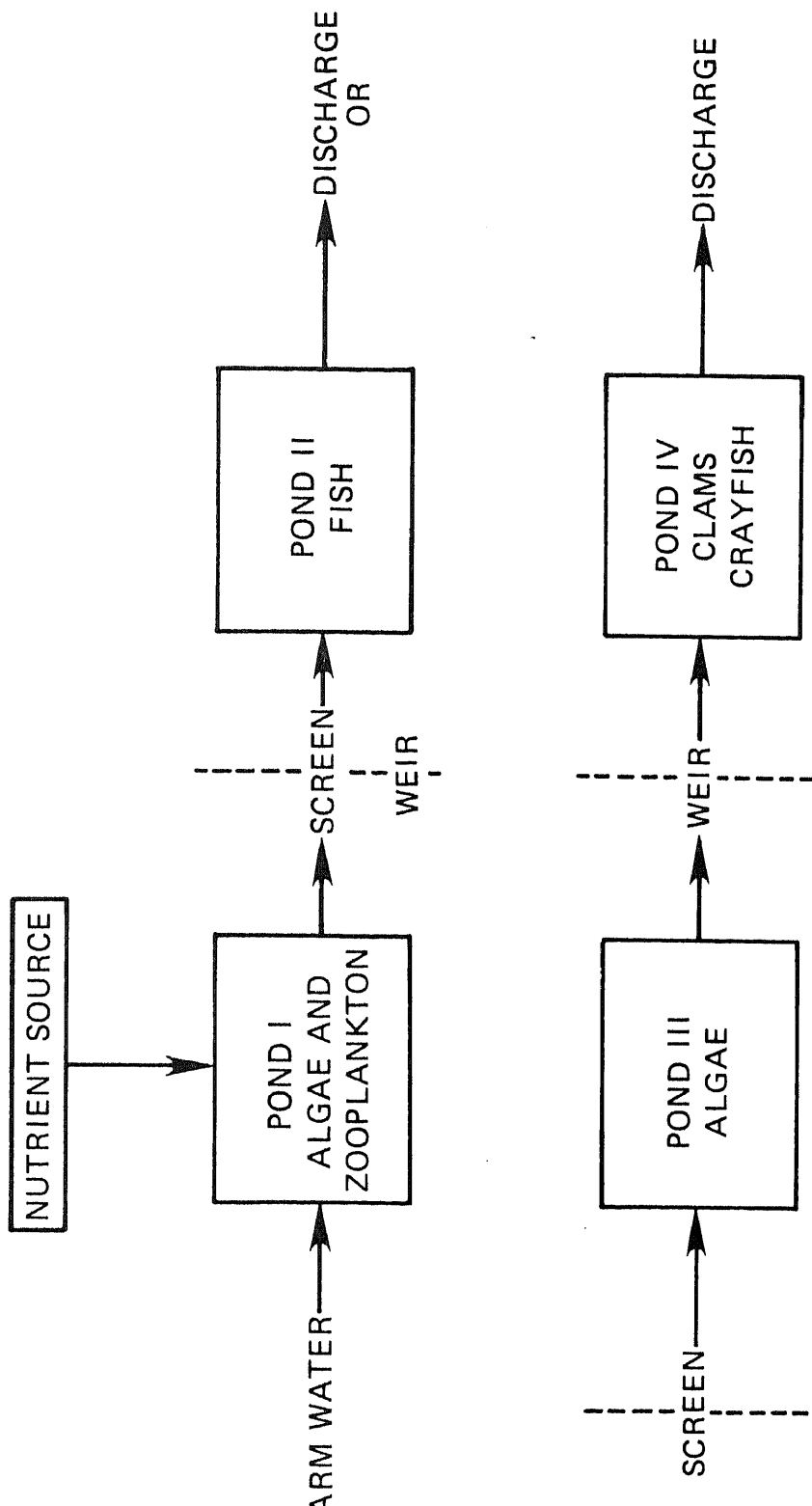


Fig. 3. Overall system schematic.

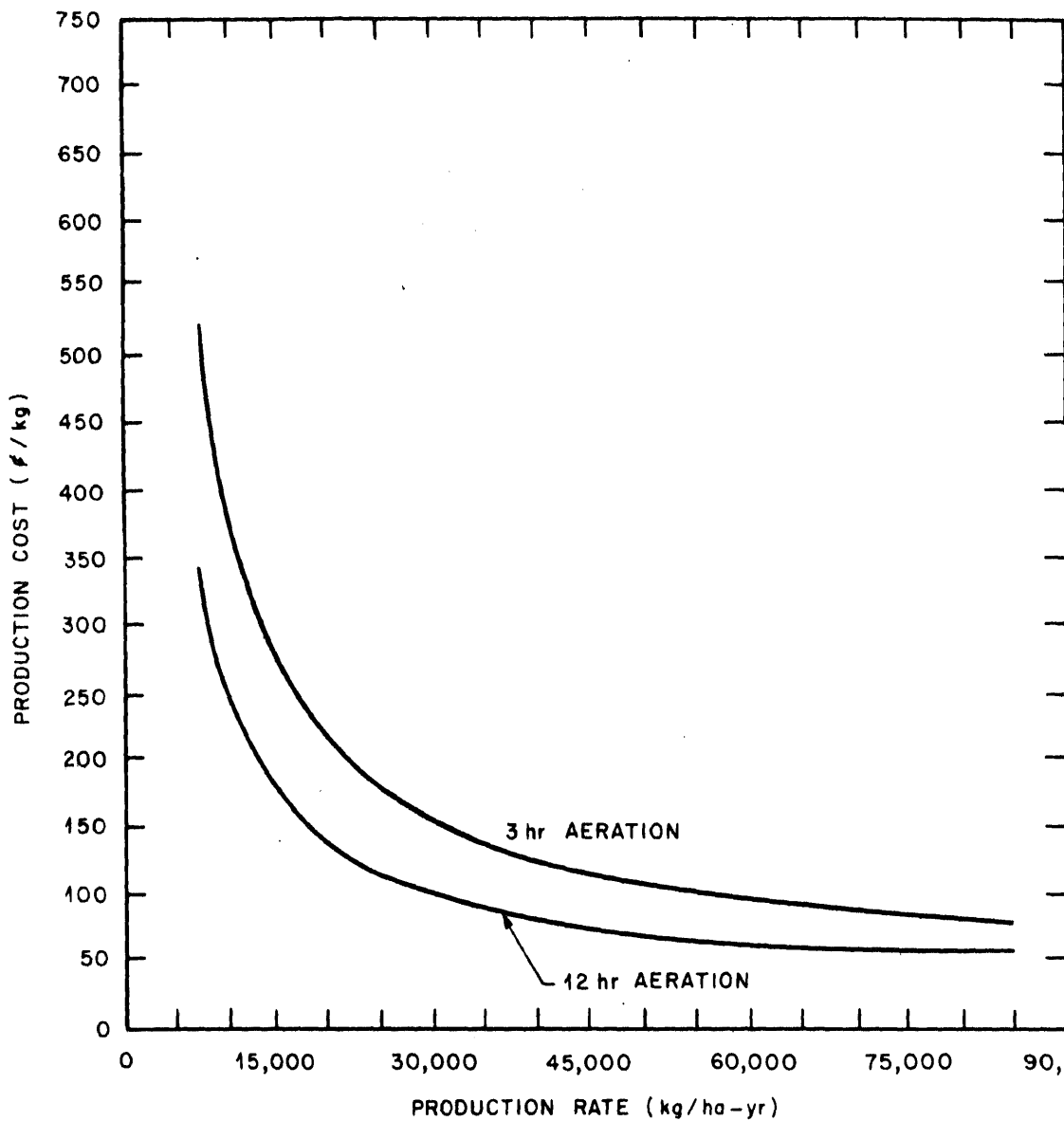


Fig. 4. Projected fish production cost for 15% fixed charge rate.

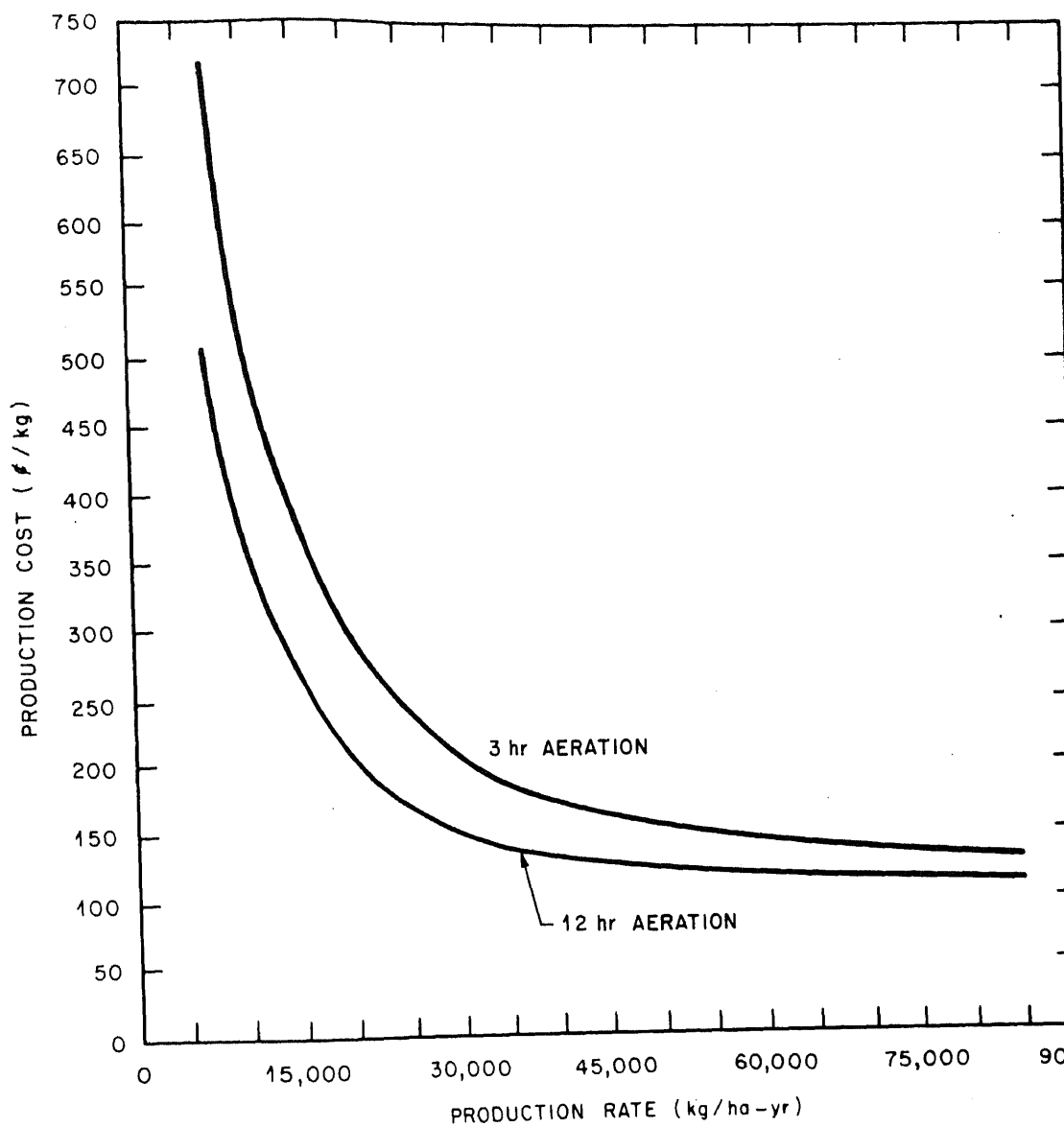
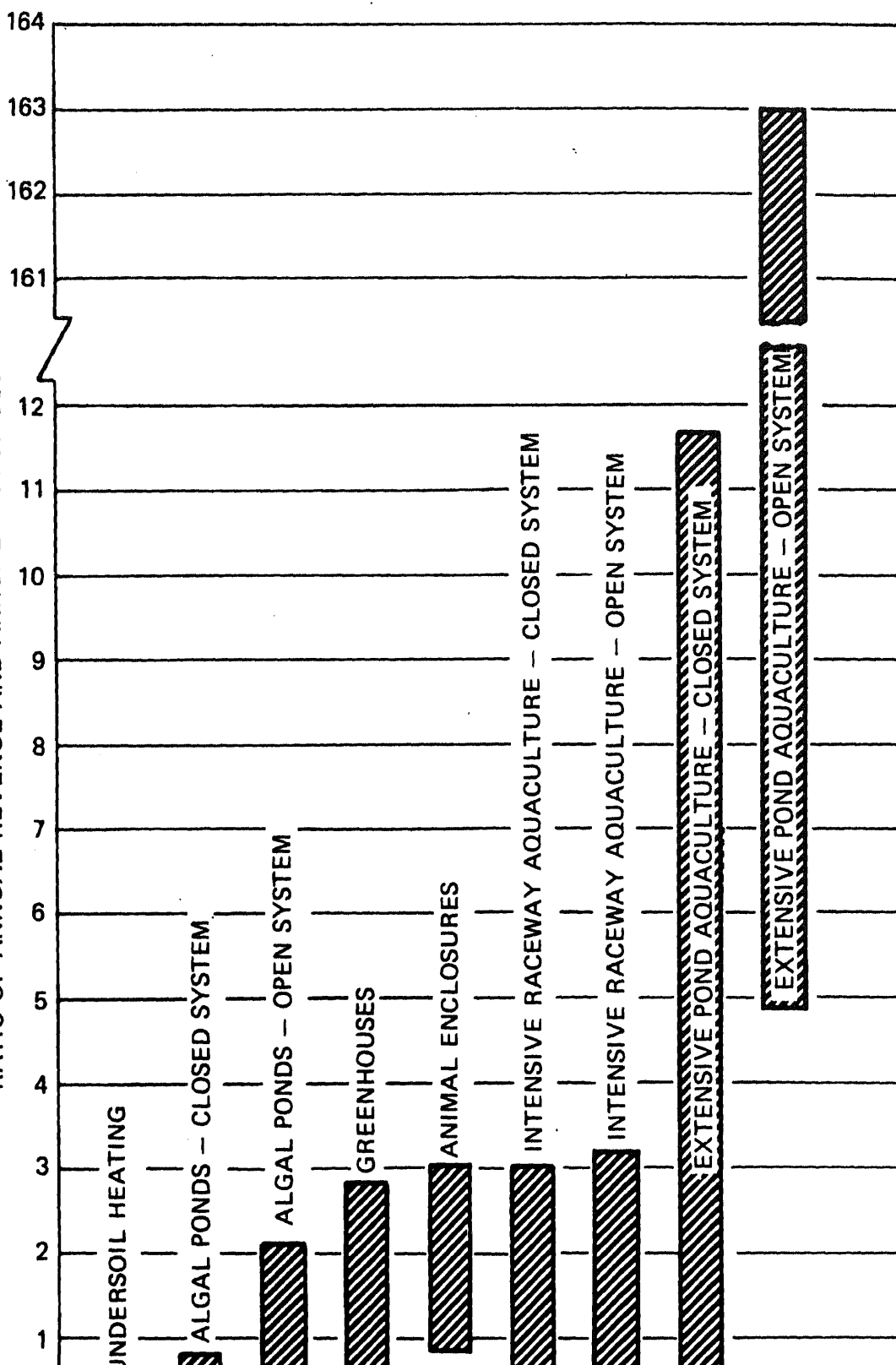


Fig. 5. Projected fish production cost for 25% fixed charge rate

RATIO OF ANNUAL REVENUE AND ANNUAL SYSTEM COST



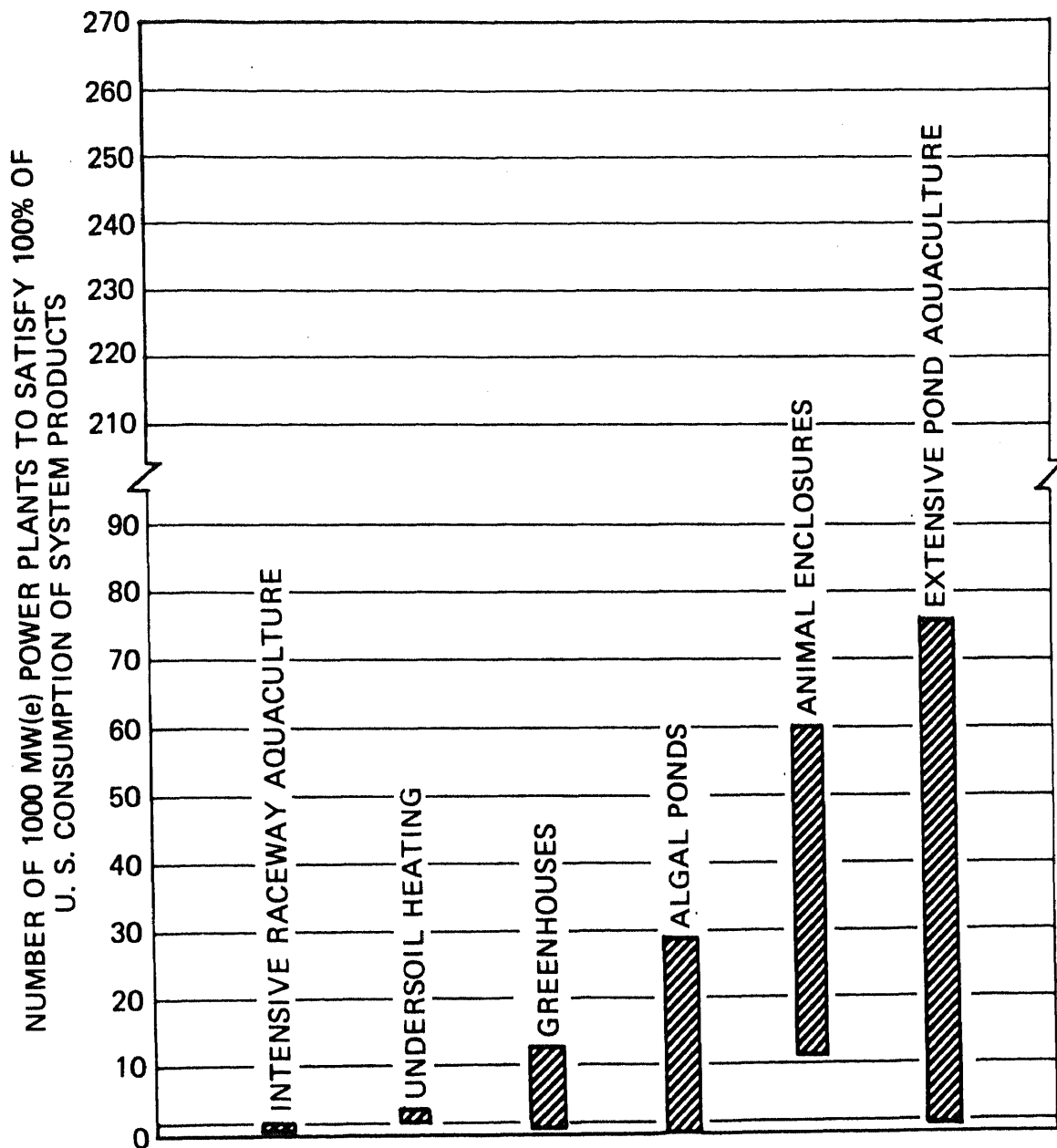


Fig. 7. Marketing index for waste heat utilization systems.

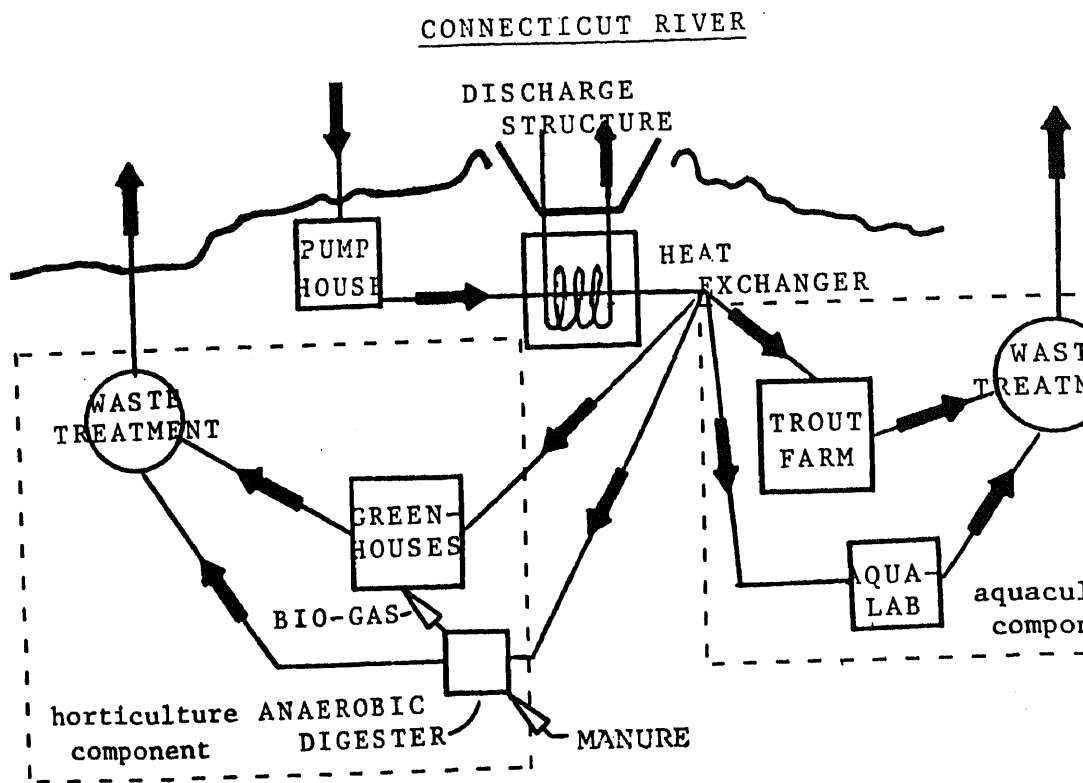
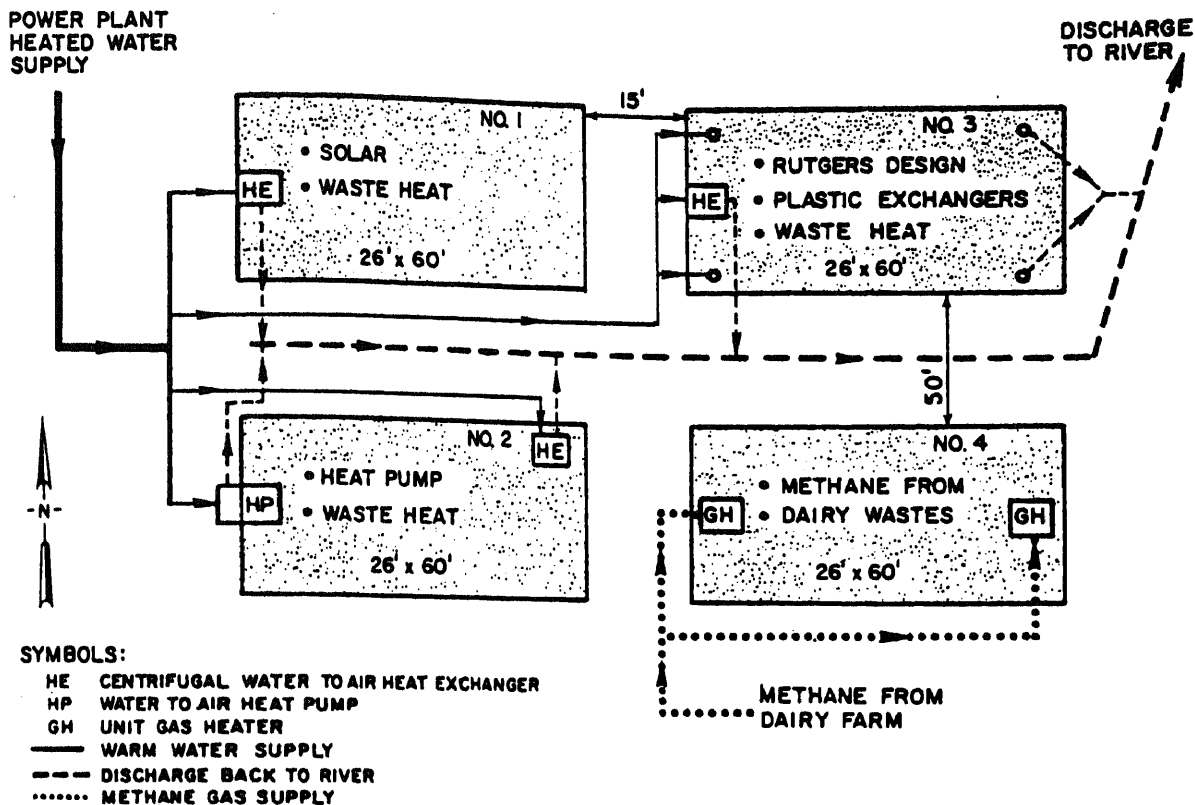


Fig. 8. Sketch of Vermont Yankee waste heat utilization concept



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